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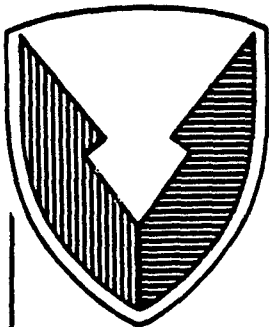
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C E N T E R

Technical Report



No. 13253

ELECTRIC DRIVE STUDY

FINAL REPORT

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Warren, Michigan 48397-5000

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19. ABSTRACT (continued)

The discussion of the concept generation and evaluation effort addresses the electric drive concept generation process and the resulting candidate concepts, the methodology used in screening the candidate concepts leading to the identification of the best concepts, and the comparison of the best concepts with conventional hydro kinetic transmissions. Thirty-eight electric drive concepts were developed for the two vehicle weight categories. Both AC and DC drives of various types and four different drive configurations were investigated.

The results of the parametric study includes trends of significant component technologies associated with electric drives, the identification of critical technologies, and projections of future electric drive system improvements relative to combat vehicle applications.

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PRELIMINARY - ELECTRIC DRIVE STUDY FINAL REPORT

1.0 INTRODUCTION

This Technical Report was prepared by General Dynamics Land Systems Division (GDLS) for U.S. Army Tank Automotive Command (TACOM) under the Electric Drive Study Contract DAAE07-84-C-R016. The contract effort was divided in three phases - Phase I Technology Survey, Phase II Concept Generation and Evaluation, and Phase III Parametric Study. The Phase I Technology Survey was a 6 month effort in which current and near term electrical and mechanical components were identified and defined that have potential in the development of optimum electric transmission concepts. A Phase I Technology Survey Report was published in January 1985. The Phase II Concept Generation and Evaluation and the Phase III parametric study efforts are the subject of this report. The document addresses the generation of candidate electric drive concepts, the analysis and screening of candidate concepts to determine the three best concepts, and the comparison of the best electric transmission concepts with selected mechanical transmissions. The electric drive concepts generated in Phase II are designed for track laying combat vehicles in the 19.5 and 40.0 ton weight categories and sized to satisfy the physical and performance requirements specified in the contract statement of work. Electric drive component technology trends and future system improvement projections developed under the parametric study effort are also discussed in this report. The parametric study effort was added to the original contract scope of work under contract modification P00006.

The U.S. Army has a renewed interest in the application of the electric drive technology to combat vehicles because recent improvements in electrical components and control methodology show promise in overcoming past drawback of electric drivetrains; namely, high weight and volume and low efficiency. The first phase of this study contract, the Technology Survey (document number JU-84-04057-002), showed the electric drive was near-term technology and that with further development, it could become a practical alternative to the conventional drive systems currently employed in track-laying vehicles. Furthermore, there exists a strong incentive for the development of an electric drive because of the many advantages that it can provide in the

typical environment and duty cycle of a combat vehicle. Unlike the current mechanical drives, the modular nature of the electric drive system and the absence of connecting mechanical drive shafts offer flexibility in drive system layout. Coupling this advantage with the potential for reduced under armor volume, an electric drivetrain makes possible a reduced vehicle target profile and/or added protective armor than are achievable with existing mechanical drivetrains. The electric drive is believed to allow more efficient engine operation because of its capability of true continuously variable operation and its ability to share on-board electric power for multiple uses. The electric drive is also believed to be more reliable and maintainable than its mechanical counterpart due to the reduction in mechanical part interfacing. Finally, power transmission in the electric drive is through motors and connecting cables rather than drive shafts and gears. This feature makes the electric drive intrinsically quieter than a mechanical transmission, helping to improve noise signature. This is desirable for a track-laying vehicle in a combat situation. In summary the significant advantages of utilizing optimum electric drive systems in combat vehicles are the following:

Flexibility in vehicle layout - improved space utilization

Multiple uses of on-board electric power

Continuously variable ratio characteristics for efficient engine operation

Improved reliability and Maintainability

Improved noise signature

In keeping with the military interest of developing combat vehicle systems with the foregoing advantages, TACOM authorized GDLS to generate and evaluate electric propulsion concepts for track-laying combat vehicles of the 19.5 and 40.0 ton categories and to identify optimum systems. The electric drive concepts generated during the contract are based on the performance and configuration requirements of the contract statement of work. Four basic electric drive configurations for which concepts were developed and analyzed are specified by the contract. The concepts that were developed and the screening analysis leading to the selection of the best concepts are described in the Discussion section of this report.

In order to illustrate the utility of an electric drive in a track-laying vehicle, the contract further required that, upon completion of the screening analysis, the best electric drive concepts be selected for a rigorous comparison to conventional drive systems. The performance and physical considerations that influenced this comparison are also reviewed in the Discussion section.

General Dynamics Land Systems has been committed to electric drive development for combat vehicles since 1981 and has drawn on this valuable experience in the execution of the electric drive study contract. This past experience includes the development of electric drive concept designs for wheeled and tracked combat vehicles for the MPWS, MPG-FT, FCCVS-I, and FCCVS-II programs. GDLS has committed a substantial amount of R&D dollars for the design, development, and test of the Electric Vehicle Test Bed (EVTB). The EVTB is a 6x6 wheeled 15 ton test bed vehicle with electric drive which at this writing is under going shake down testing.

The contract effort was augmented by the valuable experience and support of Dr. P. J. McCleer, a contracted consultant, and G. A. Fisher, and D. D. Wright of Unique Mobility, Inc., a subcontractor for the electric drive study. Also D. J. Herrera, the TACOM contracting officers' technical representative, has made important contributions to the program effort by making meaningful recommendations and supplying useful support information.

This report has been prepared in accordance with DI-S-4057 (MOD) using the TACOM R&D Technical Report Writing Style Manual No. 12680. It has been divided into five major sections: Introduction, Objective, Conclusion, Recommendation, and a Discussion of the contractual effort.

Figure 1-1 shows the program schedule that was followed to discharge the contract study. Shown are the major milestones and the three major sub-tasks of the electric drive study program.

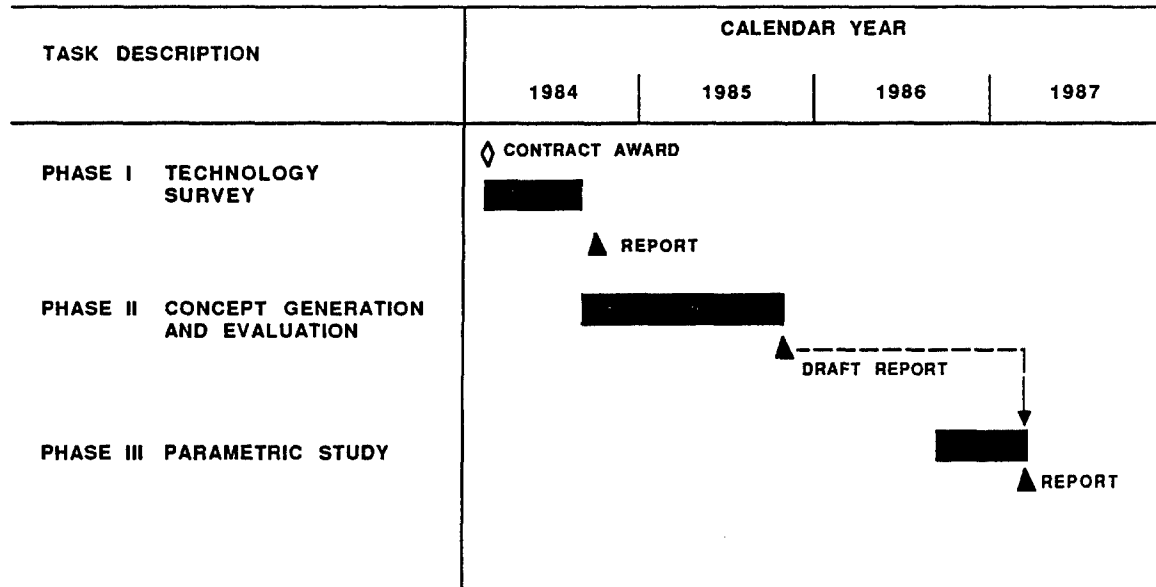


Figure 1-1. Program Schedule

2.0 OBJECTIVES

The first objective of this contract is to obtain and document data on current and near-term electric drive components that are applicable to track-laying combat vehicles of the 19.5 and 40.0 ton categories. The second objective is to develop electric drive concepts that will lead to the selection of optimum concepts for the 19.5 ton and 40.0 ton baseline vehicles and to compare the best electric drive concepts against conventional transmissions. Additionally the identification of critical technologies and projections of future electric drive system improvements are objectives of this program.

3.0 CONCLUSIONS

The evaluation of candidate electric drive concepts (totalling 38 concepts) lead to the selection of three best concepts that would offer the best potential for development as alternative transmissions in military vehicles. In the 19.5 ton vehicle class, the best electric drive concepts were:

- o Concept (I-5), a conventional DC traction motor drive developed by ACEC of Belgium using an AC permanent magnet generator.
- o Concept (I-10), an AC permanent magnet drive system developed by Garrett.
- o Concept (IV-2), a dual path AC permanent magnet drive system using traction motors developed by Unique Mobility.

The best drivetrain candidates identified for the 40 ton vehicle were:

- o Concept (I-3), and AC permanent magnet drive system developed by Garrett. This concept is similar to Concept (I-10) of the 19.5 ton vehicle class, differing only in the sizing of electrical components.
- o Concept (IV-2), a dual path AC permanent magnet drive system using traction motors developed by Unique Mobility. This concept is similar to concept IV-2 of the 19.5 ton vehicle category.

These concepts were found to be competitive with current mechanical transmissions in meeting the specified physical and performance drivetrain requirements as determined by the military vehicle type and tactical use employed in this study. In particular, the electric drivetrain was found to provide a greater flexibility in vehicle design than its mechanical counterpart. This was due to a more efficient use of the space under the armor that is made possible by the modularization of electrical components and the lack of a rigid mechanical drivetrain. As a result of this and other considerations, the study produced the following conclusions about these concepts:

- o The best electric drive concepts produce significant weight and volume savings relative to comparable mechanical transmission.
- o The best electric drive concepts can meet the tractive effort requirements for the 19.5 and 40.0 ton vehicles.
- o An electric drivetrain can be designed and operated to achieve safe and effective regenerative and pivot steering. Steer efficiency of an electric drivetrain is equal to or exceeds that of an equivalent mechanical drivetrain.
- o Propulsion efficiency of an electric drivetrain is comparable to that of a mechanical drivetrain.
- o The typical heat rejection of the electric drive concepts at 0.70 tractive effort is less than that for the mechanical drives. However, the added complexity required to cool the separate electrical modules of this system suggest that the weight and volume claim of a complete electric drive cooling system will be nearly identical to that of a mechanical drive.
- o Construction of a light weight, efficient electric drivetrain for a military vehicle is possible if near term technology is used. It cannot be satisfactorily accomplished using current off-the-shelf components.
- o Reliability and space utilization features of the electric drivetrain suggest that system maintainability and system availability may be better than currently achievable with the mechanical drivetrain.

While these advantages make the electric drivetrain attractive, developing this technology in a timely manner to fit the needs of the military vehicle remains an open question. This development risk was also factored into the study, thereby providing a further means to evaluate the concepts for acceptability. The risk analysis showed that the ACEC concept would have the least technical risk of the qualified candidates. The ACEC concept is based

on a relatively mature DC traction motor design. The Garrett concept, employing PM motors, was rated as a medium risk. The Unique Mobility concept, which employs PM motors that have undergone only limited bench testing, had the greatest technical risk of the concepts.

Other electric drivetrain concepts developed in this study showed merit for future consideration. Significant among these were the Jarret variable reluctance drive and the Westinghouse DC Homopolar drive. The variable reluctance drive requires only a single speed gear box and appears to offer significant drivetrain weight and volume reduction and improved system efficiency on the order of 84 percent. The potential advantages cited above warrant a continued examination of this concept in future work. The Westinghouse DC Homopolar drive requires minimal power electronic making it particularly attractive from a simplicity standpoint. DC Homopolar concepts scored low due to the high weight of the Homopolar motors and generator. However, if current collection can be improved and brush speed increased, then it should be possible in principle to reduce the motor weight so that this alternative would become more attractive.

The parametric study that involved the investigation of electric drive component technologies and the development of component technology trends produced the following significant conclusions:

- o The critical component technologies that will produce the most significant improvements in future electric drive systems are in the areas of power semi-conductors, permanent magnet materials, and high current brushes for current collection.
- o The technology assessment indicates minimal improvement in conventional DC drives through 1995.
- o The technology assessment indicates significant improvement in AC permanent magnet drives through 1995. These improvements include significant reduction of system volume and weight and increased system efficiency.

4.0 RECOMMENDATIONS

The following recommendations are made based on the results of the study:

1. The best electric transmission concept should be selected for proof of concept testing in a tracked vehicle test bed. The test bed should be designed so that the control concepts, hardware component designs, and related system integration questions can be satisfactorily evaluated as part of the engineering process to produce a practical and optimized electric drivetrain design.
2. The physical and operating characteristics of the variable reluctance motor drives should be thoroughly investigated and verified.

5.0 DISCUSSION

The Electric Drive Study results obtained by General Dynamics Land Systems Division (GDLS) during the contract effort are presented in this section. The background of the Electric Drive Study is discussed, the concept generation and screening methodology are reviewed, and the three best electric drive concepts for a military track-laying vehicle are identified and described in detail. The performance and physical characteristics of these candidates are then compared to those of a mechanical transmission. This comparison illustrates the advantages and disadvantages of the best electric transmissions relative to a comparable mechanical transmission.

5.1 BACKGROUND

The United States Army Tank Automotive Command (TACOM) has long expressed an interest in applying electric drive technology to military track-laying vehicles. During the 60's and early 70's, several study programs were sponsored by the government to examine the feasibility of using an electric drive in these vehicles. The studies determined that electric drives suffered serious drawbacks in size, weight, and efficiency when compared to their mechanical counterparts. Since these studies were completed, developments in electric drive technology have suggested to TACOM a need for a re-examination of this propulsion concept. As a result, TACOM engaged GDLS as a prime contractor to assist in another investigation of electric drives for track-laying vehicles. In January of 1984, TACOM awarded GDLS a contract for the Electric Drive Study (Contract DAAE07-84-C- R016). This contract was divided into two separate studies; a Phase I Survey and a Phase II Analysis.

In the Phase I Survey, GDLS conducted a thorough survey of current and near-term electrical components and technologies that could have potential application in a track-laying vehicle. Near-term components and technologies are those that can be demonstrated through proof of principal hardware by 1987. The objective of this phase was to obtain and generate data that would characterize these components and technologies sufficiently to create a basis for selection of components to be used in the detailed application analysis of the second phase of the study. As required by the contract, the nature of the

data obtained and generated reflected areas of interest to the military. These areas include the performance specifications of power rating, speed, voltage, efficiency over operating range, and torque over operating range. Other areas considered in the survey were component volume, technical risk, weight, reliability, and safety.

The survey was successfully completed by GDLS in July, 1984 and is summarized in Report No. JU-84-04057-002. The data presented therein allowed the following conclusions to be drawn:

- o Electrical components and technologies have progressed greatly in recent years to offer better reliability, improved performance, and consolidated packaging for electric drive propulsion.
- o Electric drive technology is developing at a pace and in a direction compatible with near-term development of track-laying combat vehicles.
- o A wide variety of electrical components are currently available to construct an electric drive system.

Using the data collected in the Phase I Survey, GDLS generated and studied various electric drive concepts as required to obtain an optimal system for the 19.5 ton and 40 ton track-laying vehicle. This activity is the second and final phase of the contract study and is the subject of this report.

Sections 5.2 and 5.3 review in detail the methodology used for generating, and screening the candidate electric drive concepts leading the selection of the best three concepts. Section 5.4 describes the operational and performance characteristics of the best three concepts. Section 5.5 addresses the ability of these candidates to compete favorably with the mechanical transmissions in the 19.5 ton and 40 ton track-laying vehicle class. Section 5.6 describes the conduct and findings of the recently awarded (1986) parametric study. This study predicts technology trends associated with electric drive components and accesses the impact of these technology developments on the physical and performance characteristics of the electric drive in the track-laying combat

vehicle. Section 5.7 discusses the prospects for alternative technologies that, if successfully developed, could further enhance the attractiveness of an electric drive in future track-laying combat vehicles.

5.2 CONCEPT GENERATION

The electric drive components and concepts that were identified during Phase I Technology Survey were used to generate concepts for four basic drivetrain configurations which were stipulated by the contract. Variations of concepts and of component combinations were investigated to insure that as many alternatives as practical were investigated in the quest for the optimum electric drive system.

Thirty-eight candidate electric drive concepts were generated and are described in this section. The requirements that governed the concept generation and the approach to concept design are presented. Estimates for cooling, gear, and brake subsystems, that were developed and used in the concept generation process are also discussed.

5.2.1 Requirements

The electric drive concepts generated for the 19.5 and 40 ton baseline vehicles were developed and sized to satisfy the requirements outlined in the contract vehicle specification. The 19.5 and 40 ton vehicle specifications are presented in appendix A. These address the physical characteristics and power requirements of the propulsion, steer, braking, cooling, and auxiliary systems. The Cummins VTA-903T engine and the AD-1000 engine are specified as the prime movers to be included in propulsion system concepts for the 19.5 and 40 ton vehicles.

5.2.2 Configurations

Four basic drivetrain configurations provided a useful guideline for developing the 38 candidate electric drive concepts. These configurations were specified by the contract specification and served to assure that certain

electric drivetrain alternatives would not be overlooked. In addition to these four basic configurations, GDLS deemed it necessary to modify Configuration I to generate another electric drivetrain configuration called Configuration 1A.

5.2.2.1 Configuration I

Configuration I involves an engine-driven alternator and individual traction motors located at each drive sprocket. The traction motors may be selected and sized for either direct sprocket drive or for indirect sprocket drive using an intermediate gearbox. Figure 5.2-1 shows a schematic of Configuration I, with gearbox located between the drive motor and sprocket. The alternator output is conditioned by individual power conditioning units (PCU), thus providing power of the appropriate voltage and frequency to each traction motor. The electronic control unit (ECU) coordinates the entire electric propulsion system in accordance with operator commands and system feedback information.

Configuration I uses two independent traction motor drives, one at each track, to provide the required tractive effort. This design facilitates separate control of each track, thereby providing excellent vehicle control during propulsion, steering, and braking. The ability of the motor PCU to operate bilaterally makes this control possible, in that the PCU allows power flow to the motor when vehicle forward/reverse propulsion is required or power flow from the motor operating as a generator (regeneration), during periods of braking or steering. The bilateral nature of the PCU allows regeneration of power from the inside track to the outside track during steer maneuvers, a requirement of modern transmissions for track laying vehicles. However, to take full advantage of this regenerative feature, the traction motors and PCUs must have a short time duty rating adequate to handle the increased electrical load during regeneration which can exceed 3 times the continuous duty rating.

Configuration I offers exceptional potential for providing the more desirable rear sprocket drive with a rear entry cargo compartment. Also, this configuration is believed by GDLS to offer the least complex vehicle installation relative to other configurations.

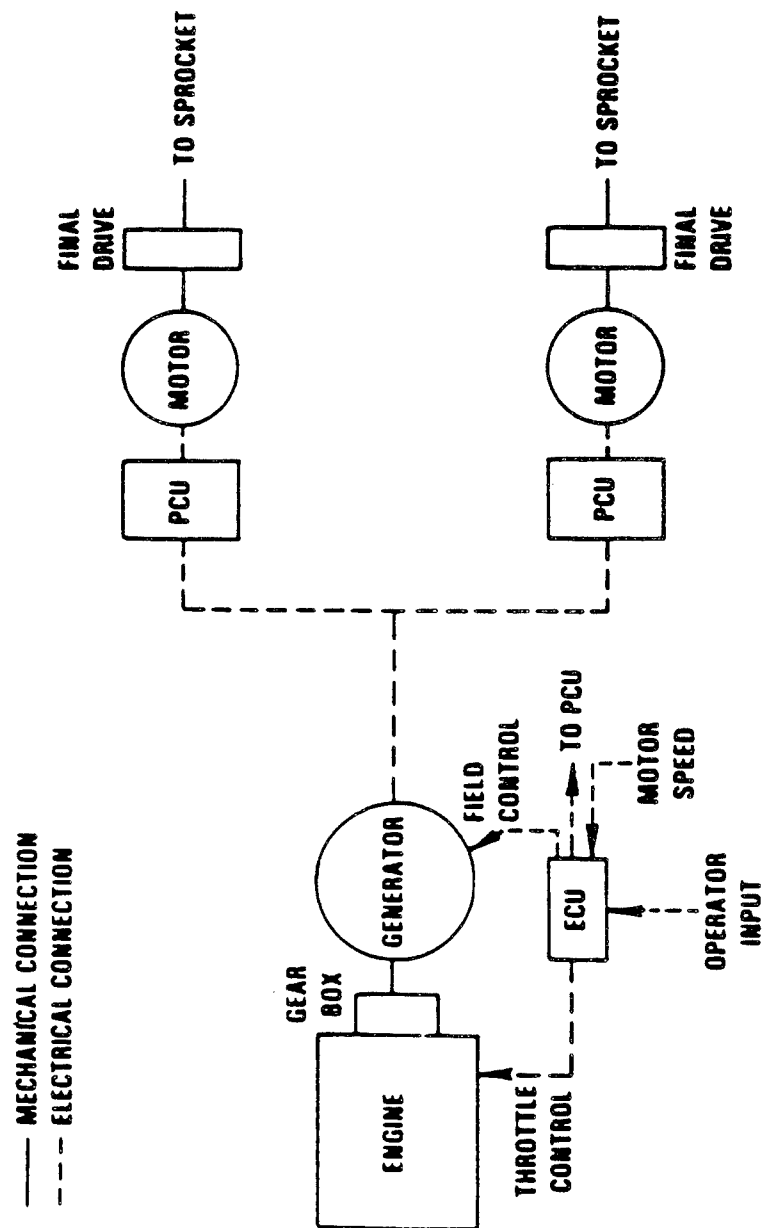


Figure 5.2-1. Configuration I Schematic:
Individual Motors and Drives for Each Sprocket

5.2.2.2 Configuration IA.

This configuration is similar to Configuration I with the single exception that the traction motors and gearboxes are mounted inside four drive sprockets (two rear and two front sprockets). This is accomplished by increasing the number of traction motors from two to four thereby lowering individual motor power rating and space claim. Because of this change, the space claim of the drivetrain components under the armor is reduced; however, the complexity of the system is increased due to the increased number of drive units.

5.2.2.3 Configuration II.

Configuration II uses one motor coupled to a cross drive to provide the propulsion effort and a separate motor driven cross drive for steering. The power for the propulsion and steer drives is provided by an engine-driven generator where output is conditioned by power conditioning units. Figure 5.2-2 shows a schematic of this configuration.

Configuration II differs from Configuration I in that a single, higher power motor is used to provide all vehicle propulsion. Steering is accomplished by the steer motor and the propulsion motor working in combination. Pivot steer is accomplished solely by the steer motor.

Space saving is possible with this configuration because the propulsion motor and PCU intermittent power ratings can be reduced, due to the mechanical feedback path. Also the need for a two speed gearbox at each drive sprocket is eliminated. The disadvantage of this configuration is that the steer cross shaft and propulsion cross shaft have a negative impact on design flexibility.

5.2.2.4 Configuration III.

Configuration III is similar to Configuration I except that a mechanical feedback path with steer motor is used to regenerate power for steering. Propulsion motors and PCU intermittent ratings can be reduced as in Configuration II. Configuration III, shown schematically in figure 5.2-3,

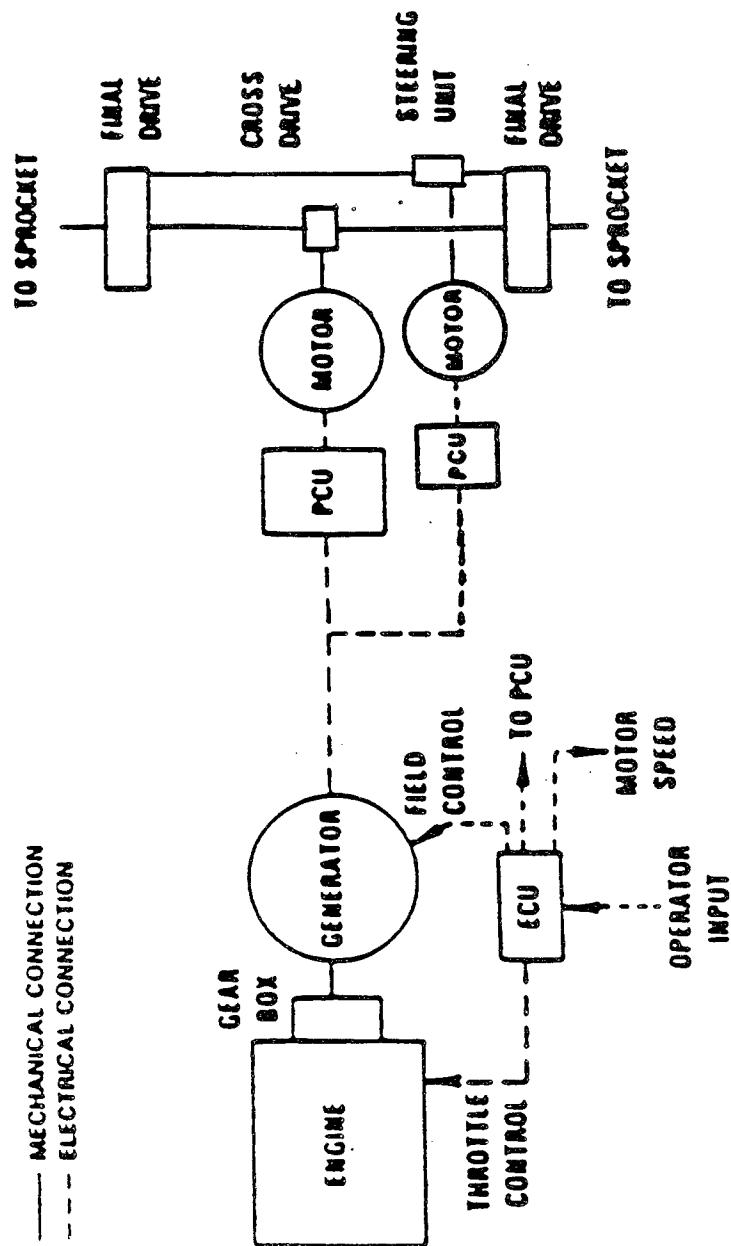


Figure 5.2-2. Configuration II Schematic:
Single Motor Crossdrive Electric Transmission

uses an engine-driven alternator with electric motors at each sprocket driving the final drives. Also shown is the mechanical feedback path for steering regeneration.

5.2.2.5 Configuration IV.

Configuration IV, shown in figure 5.2-4, is an electromechanical, dual power path drive where electrical and mechanical power are summed at combining planetary gears in the final drive units.

An operational advantage of this configuration is that it simplifies the matching of operating speeds to torque by balancing the load carried in the respective electrical and mechanical transmission path. Additional advantages have been identified in this configuration. These are:

- o Reduced intermittent power rating for traction motors and PCUs.
- o Increased transmission efficiency when mechanical path is operative.

5.2.3 Concept Design Approach/Guidelines

The objective of the concept generation task is to develop electric drive concepts that will lead to the selection of optimum concepts for the 19.5 ton and 40.0 ton baseline vehicles. Various concept, using AC and DC machinery with varied power conditioning schemes, were developed for each drive train configuration (see section 5.2.4) and for each vehicle weight category to insure that all practical alternatives were considered in the quest for optimum concepts. Concepts were generated from three different areas:

- o Electric drive components identified in the Phase I technology survey.
- o Concepts offered by manufacturers.
- o Variations on the above concepts.

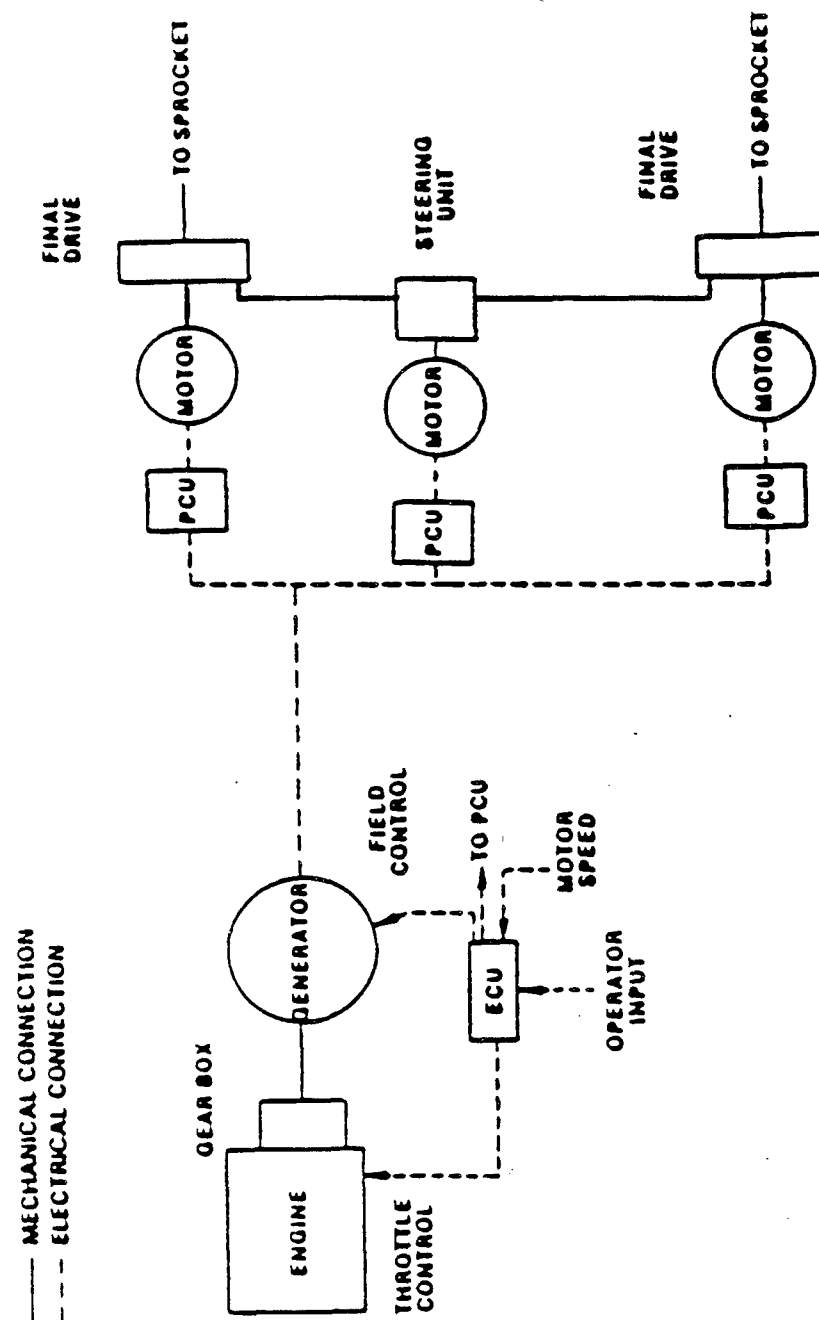
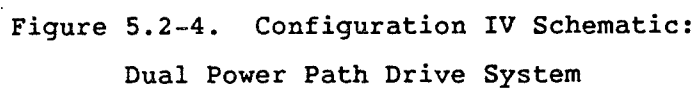


Figure 5.2-3. Configuration III Schematic: Individual Sprocket Motors with Mechanical Regenerative Steering



To minimize the number of electric drive concepts developed, the effort initially concentrated on concepts for the 19.5 ton vehicle. Later 40 ton vehicle concepts were selectively developed based on trends established from 19.5 ton concepts. Also, due to the large number of concepts generated and evaluated, analysis of concepts was conducted only to the extent necessary to establish the relative merit between concepts.

Detailed analysis was reserved for the best three concepts whose selection was based on the results of the concept screening process discussed in section 5.3.

The transmission components were sized to meet the physical and performance requirements of the contract vehicle specifications presented in appendix A. The electric machinery was sized to provide the specified tractive effort rather than being based on net power available to the transmission and the transmission concept efficiency. Many concepts generated could not provide the specified tractive effort at the sprocket over the vehicle speed range due to lower than required transmission efficiency. A transmission efficiency of approximately 85 percent (including final drive) is needed to delivery the required tractive effort to the sprocket. Table 5.2-1 presents the full load parasitic and auxiliary losses that were used to determine full load net input power for transmission concepts of the 19.5 and 40.0 ton vehicle categories. The Cummins VTA-903T engine is specified as the prime mover for the 19.5 ton vehicle and the AD-1000 advanced diesel engine is specified for the 40 ton vehicle.

Electric drive concepts were generated using the following design guidelines.

- o Satisfy performance requirements.
- o Provide regenerative and pivot steer capability.
- o Provide two separate brake systems for redundancy during emergencies.
- o Provide adequate cooling at 0.7 GVW tractive effort and 120°F ambient air temperature.

- o Minimize system volume.
- o Minimize technical risk.
- o Minimize system weight.
- o Maximize system efficiency.
- o Reduce complexity.
- oo Concepts without multiple speed gearbox preferred.
- oo Reduce electronic power conditioning.

TABLE 5.2-1. ENGINE NET POWER AVAILABLE TO TRANSMISSION
AT FULL LOAD

	<u>19.5 Ton</u>	<u>40.0 Ton</u>
Gross Engine HP	500	1000
o Deduct 2% for induction & exhaust losses	-10	-20
o Deduct 12% for cooling power	-60	-120
o Deduct for auxiliary power requirements	-3	-5
Net power available to transmission	427	855
	(318 KW)	(637 KW)
Power desired at sprocket	365	730
Transmission efficiency required to meet desired power at sprocket	85.5%	85.4%

The following discussions address the evolutionary process for generating electric drivetrain concepts. The process starts with the consideration of various electric machines leading to the formulation of complete electric drivetrains. Included in the discussion on electric machines are two innovative machines (the AC homopolar and the outside rotor PM synchronous machines) which exhibit some highly desirable features and hold promise for electric drivetrains. Transmission subsystems including brake systems, cooling systems, and gear systems are also addressed.

5.2.3.1 Electric Machines

Since all electrical machines are inherently capable of operation as either motors or generators we do not group or identify the machines according to application. Rather, we group according to DC or AC electrical power flow and according to the manner in which torque producing rotor flux is generated. We also do not group by packaging techniques (i.e., conventional rotor vs. pancake or disc machines).

Figure 5.2-6 is a "family tree" of large electrical machines that are potential candidates for inclusion in vehicle electric drive systems. In general, the foremost distinction between AC and DC machines, excluding the AC homopolar machine, is the fact that the full machine line current must be "wired" through brushes to the rotating element of a DC machine while the full machine line current connects only to the stationary member of an AC machine. This attribute alone is a major potential advantage for AC machines. It must be carefully weighed, however, particularly with respect to PCU requirements before a choice between DC or AC machinery can be recommended.

AC Machines.

AC Synchronous: Wound Rotor. Wound rotor synchronous machines can be further subdivided into smooth (cylindrical) and non-smooth (salient pole) rotor machines. Smooth rotor machines are in general of higher speed and lower in pole order when compared to salient pole machines. Both versions traditionally have the DC rotor field current supplied through sliprings,

though brushless versions are becoming more and more commonplace. In this version, electrical commutation is made by using an auxiliary permanent magnet (PM) AC alternator with rectified outputs feeding inside-out AC generators with rotating rectifiers. The rotor in a synchronous machine follows or leads in synchronism the rotating magnetic field induced by multi-phase stator winding currents. To use any form of a synchronous machine as a variable speed motor, a variable frequency supply must be used in conjunction with a shaft position sensor.

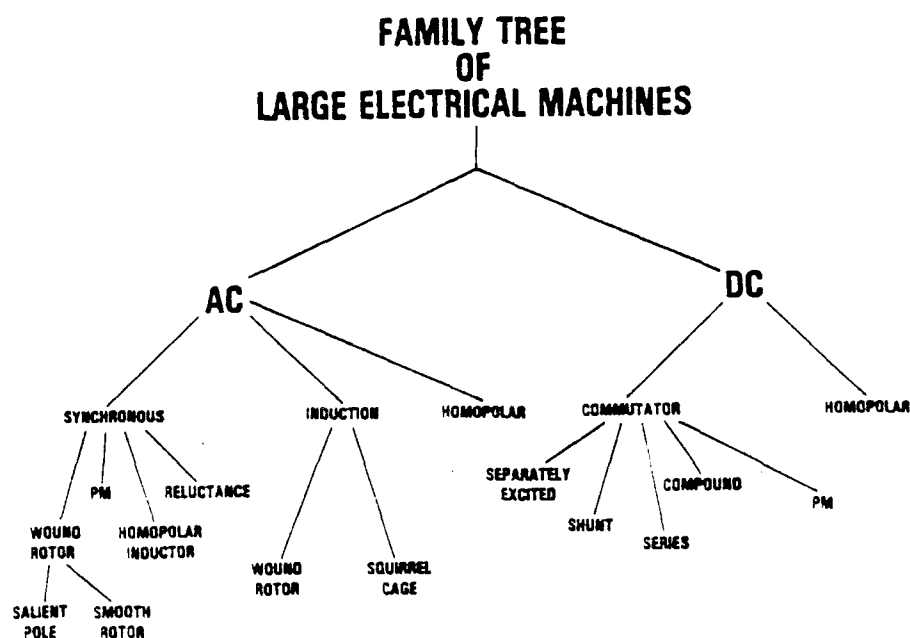


Figure 5.2-6. Family Tree of Large Electrical Machines

AC Synchronous: PM (permanent magnet). This machine, also referred to as a "brushless DC machine," is almost identical to the wound rotor synchronous machine; the principle difference being in the production of the DC field flux by a rotating permanent magnet rather than be a slipring supplied field coil. These machines have only recently come to the forefront of the list of candidate machines for vehicle electric drives. With the commercial introduction of rare-earth permanent magnets, particularly samarium-cobalt alloys with energy products (BH) of five times those of previous materials, these machines quickly became prime contenders for traction motors in high performance AC vehicle drive systems. PM synchronous machines are used in the GDLS EVTb.

AC Synchronous: Homopolar Inductor. The rotating DC field in this machine is supplied by a store mounted field coil and a unique two element ferromagnetic salient pole rotor. The rotor poles essential "pull" the radial components of the field flux around the inner surface of the stator structure inducing voltages in the distributed stator windings. The field flux paths are completed through axial paths in the rotor and the stator. From the stator terminals the machine appears as a standard synchronous machine. The principle advantage of this machine is the lack of field winding brushes.

AC Synchronous: Reluctance. If the DC field winding in a salient pole synchronous machine is open circuited the machine will continue to produce torque in the motoring mode or electrical power in the generating mode, though at a level somewhat lower than that produced by operation utilizing the field winding. A torque is produced to maintain a minimum energy system and to keep the rotor magnetic poles in synchronism with the rotating magnetic field produced by the multiphase currents in the stator windings. The reluctance machine is similar in construction to the wound rotor salient pole synchronous machine, the principle difference being its complete lack of a rotating field winding. The advantage of this machine is the lack of steady-state rotor losses but the disadvantage is the lower available power from the same frame size when compared to a machine that supplies DC rotor flux.

AC Induction. Induction machines produce rotor winding currents through transformer action between the rotor and store windings. Machines with separate multi-phase rotor windings brought out to the frame via sliprings and brushes are referred to as wound rotor machines, while machines with circumferentially symmetric shorted bar rotor conductors are referred to as squirrel cage machines. Squirrel cage induction motors are the work horses of industry, comprising more than 90% of all integer horsepower electrical machines manufactured. Until the advent of the PM synchronous machine no machine compared in ruggedness and reliability to the squirrel cage induction machine.

DC Machines.

A DC commutator machine can be envisioned as an inside-out (field on a stationary frame with power windings on the rotor) AC synchronous machine in

which the shaft position sensor and variable frequency switching network are combined in the commutation contacts on the rotor. The switching action of the commutator maintains the magnetic field of the rotating power windings or armature windings stationary in space in magnetic quadrature with the flux of the field windings and enables unidirectional torque production. The different classifications of the DC commutator machines are derived from the methods of field flux production or field coil connection. The separately excited machine has an entirely separate power supply to excite the field winding. The shunt winding machine has its field winding connected in parallel or in shunt to the armature and to the load (generator operation) or main supply (motor operation). The series winding machine has its field winding connected in series with the armature and must be capable of passing full load current through the field coil. The compound machine has both shunt and series field windings and has characteristics that bridge those of the shunt and series machines. The permanent magnet or PM machine requires no field winding as its field flux is supplied by permanent magnets.

Innovative Machines.

The electrical machines described in the previous two sections can be termed traditional or standard or AC or DC motors and generators. With the exception of the PM synchronous machine, these motors and generators have been in production for many years.

Recently, potentially innovative electrical machines have been advanced by three different groups as candidates for vehicle electric drivetrain elements. These machines are: the DC homopolar machine, the AC homopolar machine, and the outside rotor PM synchronous machine.

The DC homopolar machine, figure 5.2-7, is the simplest electromechanical machine possible and was in fact the first electrical machine ever constructed (Faraday, 1831). However, it has only recently been considered in drive applications due to advances in liquid and solid high current density, collection systems. DC field flux passes through a rotating disk, figure 5.2-7, or, more usually, a rotating drum and induces a DC electromotive force (EMF) in a direction normal to both the field flux path and the direction of

rotation. The collector brushes, solid or liquid metal, couple the active disk or drum to a load (generator) or a DC source (motor). No commutator action is needed and the machine is capable of operation at very high speeds. The generated EMFs are of very low magnitude, tens of volts, even at mechanically limiting rotational speeds and magnetic material limiting field flux densities, so the machine is a low voltage, very high current device. Using this low voltage machine in an electric drive system would be advantageous from an insulation and safety standpoint. However, the very high operating current level would require large power cables (power bus) to guard against conductor overheating and subsequent failure. The increased IR heat production associated with the high current operating level also suggests that forced cooling of the power bus system may be required.

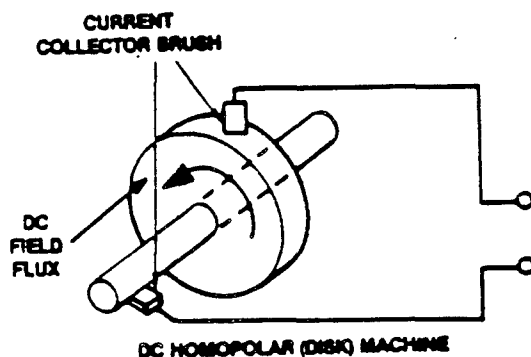


Figure 5.2-7. DC Homopolar Machine

The AC homopolar machine, figure 5.2-8, is the recent invention of Dr. L. J. Giacolleto and is currently under development at the University of Michigan, under U.S. Army TACOM support. The machine consists of spinning metallic disk rotors under axial AC flux excitation. The AC field flux is supplied by stationary circumferential field windings supplied by a lower power AC field oscillator. Field flux cut by the spinning disk faces induce electromotive forces (EMF) in the radial direction within the disks. Brush contacts, liquid metal or solid, at the outer edge of the disks collect load current with the other conducting path being the shaft of the machine that supports the disks.

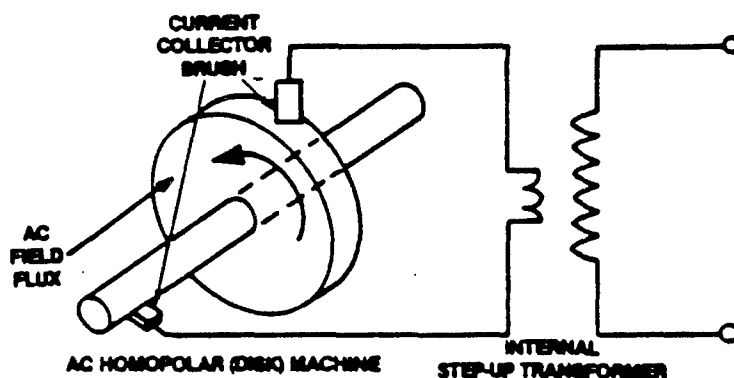


Figure 5.2-8. AC Homopolar Machine

The machine is unique in that it also contains an internal step-up transformer so that the machine electrical terminals experience high voltages and moderate currents as opposed to the low voltages and very high currents that are characteristic of DC homopolar machines. The advantages of the machine are its high power density and its ability as a generator to supply a variable frequency output whose frequency is not dictated by the shaft speed of the prime mover.

A novel PM synchronous AC machine, figure 5.2-9, has recently been developed by Unique Mobility, Inc. of Englewood, Colorado. This machine has an inverted structure in which radially directed permanent magnets are mounted on a hollow cylindrical coaxial rotor structure providing a magnetic flux outer return path that rotates around the outer surface of an also hollow stator structure, hence the name "outside rotor." The hollow stator structure has its multi-phase axially directed power windings very close to the air gap surface for enhanced winding heat loss removal and utilizes radially oriented - grain magnetic material for enhanced magnetic flux production. In addition to the outside rotor structure that supports the permanent magnet, the rotor has an inner hollow coaxial magnetic flux return cylindrical structure that, along with the outside rotor, coaxially sandwiches the radially thin stator. The totally hollow structure save for the shaft, has a minimum amount of magnetic material (iron) and therefore has the potential for very high power per weight (power density) performance. The hollow space in the stator may be used to house a final drive gearbox and thus the machine potentially offers a volume savings as well.

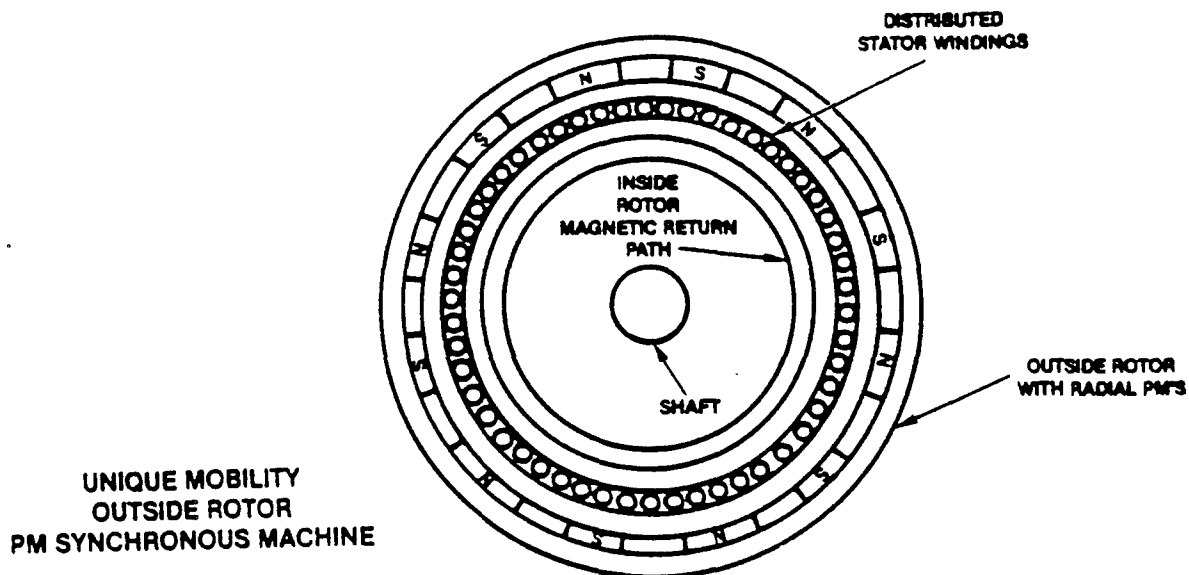


Figure 5.2-9. Unique Mobility Machine

5.2.3.2 Electric Drivetrain Configurations

For a tracked vehicle, two traction motors are typical but there are designs for as many as six and as few as one. A single power conditioning unit can be used with each motor or with each pair of motors but it is also possible to configure electric drive systems that employ no power conditioners, thus eliminating the need for very high power semiconductor devices that must pass the full traction power of the vehicle. The number of possible combination of drive train components using the electrical machines discussed in section 5.2.3.1 is almost unlimited, however, practical considerations narrow the field to a reasonable number. Figures 5.2-10 and 5.2-11 show several possible "generic" DC (DC traction motor) and AC (AC traction motor) drive concepts.

AC machines have long been recognized as possessing superior qualities when compared to similarly rated DC units. AC machines, compared to DC machines, are in general lower in cost, lower in weight, lower in inertia, higher in efficiency, more rugged, and more reliable and able to operate in harsher environments. The emergence of AC variable speed drives, driven by the desire to capitalize on these attributes, has been made possible by the development of high power semiconducting switching devices. Yet it is these very devices, the power semiconductors that make AC drives possible, that have thus far limited the economic introduction of AC variable speed vehicle drives. Rail traction, large earth moving machine, and the fledgling electric car industry all remain in the DC camp. Past hardware demonstrations of military AC drive vehicles have all been hampered by the inability to obtain semiconductor power devices that would allow the electric drive vehicle to match or exceed the performance of the mechanical drive counterpart. Semiconductor power devices have dramatically improved over the last 5 year and are now capable of providing the required performance.

All the drive concepts shown in figures 5.2-10 and 5.2-11 assume two traction motors each, but the drive principles would not be changed if this number were to be changed. The obvious advantage of at least two traction motors is the potential of regenerative steering, using the electric bus to transfer steering power from one track to another.

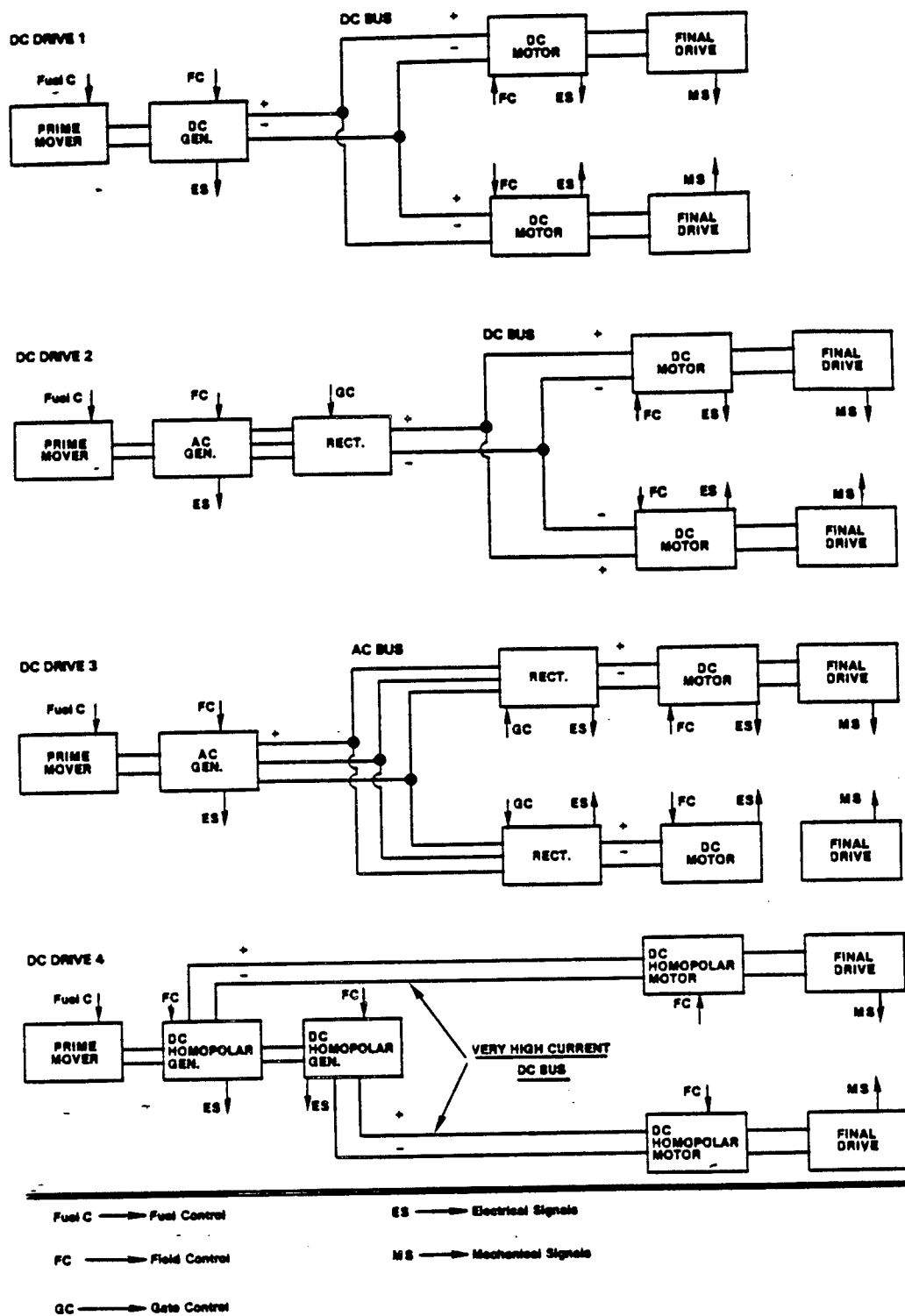


Figure 5.2-10. Various DC Drive Systems

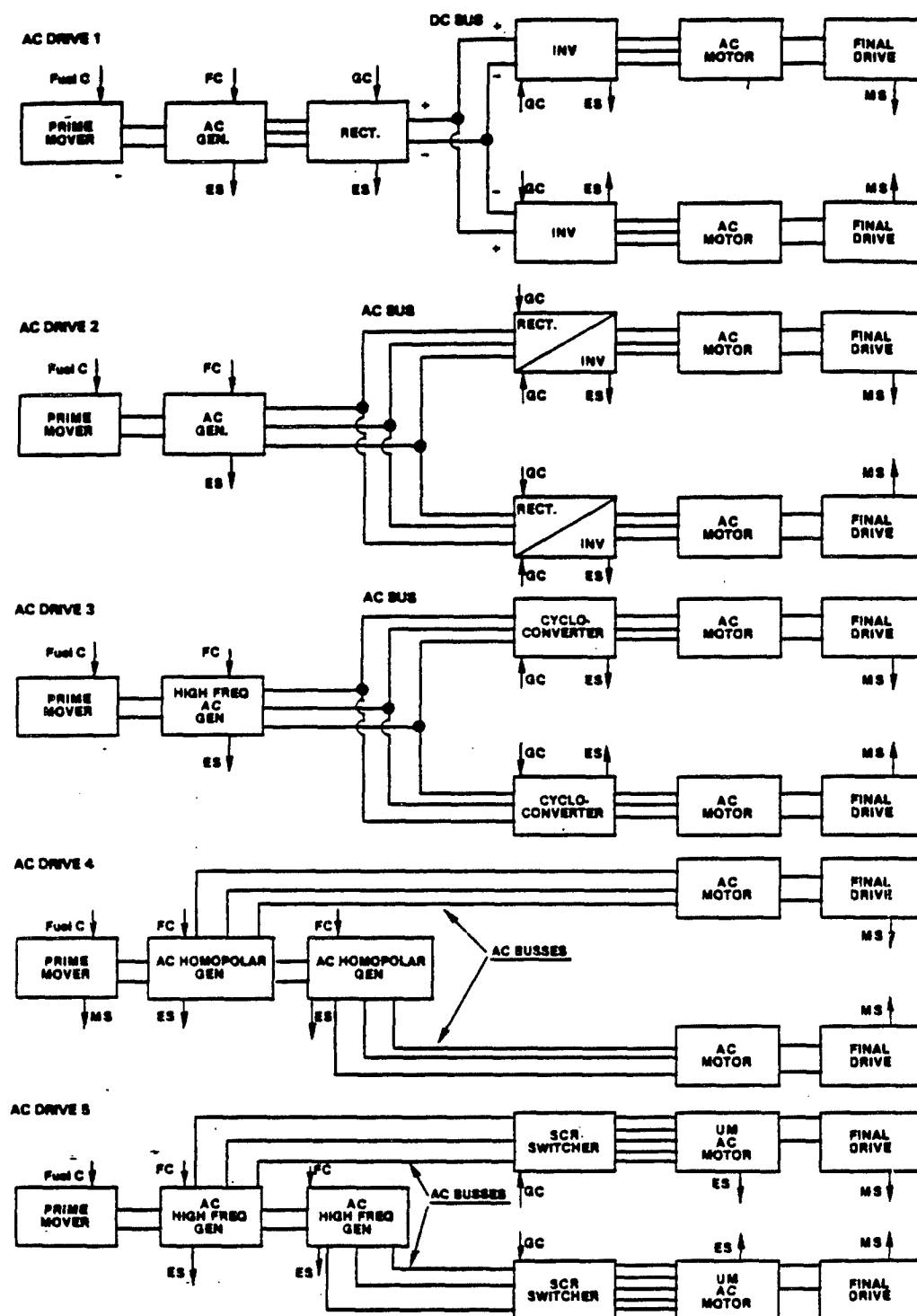


Figure 5.2-11. Various AC Drive Systems

Not shown in figures 5.2-10 and 5.2-11 are brake resistors that could be switched in to provide dynamic braking capability. These resistors would be electrically located such that they could be switched in across the electrical power buss that distributes the traction electrical power from the main generator to the traction motors. Operating the traction motors as generators enables the vehicle kinetic energy to be absorbed either with the prime mover operated in the braking mode with the main generator operated as a motor, or with the braking resistors across the electric power bus, or in both, again all under electronic control.

DC Drive 1 is the most basic drive system. No PCU is required, only field control of the generator and the traction motors. Series field traction motors can be used but require large contactors to reverse the field current on the inboard track motor for steering control.

DC Drive 2 is similar to Drive 1 except that a rectified DC generator is used to feed the DC power bus. U.S. Army MERADCOM recently (fall, 1982) completed a conceptual design study for David Taylor, Naval Ship Research and Development Center on such a drive for use in a Marine Corps amphibious tracked vehicle.

DC Drive 3 differs from Drive 2 in the bussing of the traction electrical power. Here an AC bus is used to distribute the output of the DC generator to separate controlled rectifiers which in turn feed the DC traction motors.

DC Drive 4 is a unique drive concept presently under study at the David Taylor Naval Ship Research and Development Center for use in amphibious vehicles. The use of homopolar machines is a spin-off from the superconducting DC homopolar machine work done at David Taylor for use in ship propulsion.

AC Drive 1 and Drive 2 (figure 5.2-11) differ in the bussing of the electric traction power from the AC generator to the AC traction motors. AC Drive 1 uses a single controlled rectifier to feed a DC bus while AC Drive 2 employs an AC bus feeding individual rectifier/inverter sets.

GDLS has considerable experience (FCCVS, MPWS, MPT-FT, and EVTB) in these two particular AC drive concepts. The power inverter units used in AC Drive 1 and AC Drive 2 are the chopper/inverter and the converter/inverter.

The chopper/inverter configuration (figure 5.2-12) consists of an input capacitor filter, transistor chopper, free wheeling rectifier, inductor filter, and thyristor inverter. The input capacitor filter serves as a low impedance voltage source for the transistor chopper and suppresses the high frequency current component present in the DC link. The chopper serves to modulate the incoming voltage level as a function of command-constrained power demand. The free wheel rectifier, with the help of the inductor, maintains a continuous motor current in the chopper-off periods. The thyristor inverter is a line commutated type, whereby the thyristors are turned off by the back EMF of the motor(s). At speed conditions below 10% rated, when the back EMF is too low to affect thyristor turn-off, a low frequency modulation (blanking) is imposed to provide forced commutation. The chopper/inverter type PCI is fed from a DC bus as in AC Drive 1.

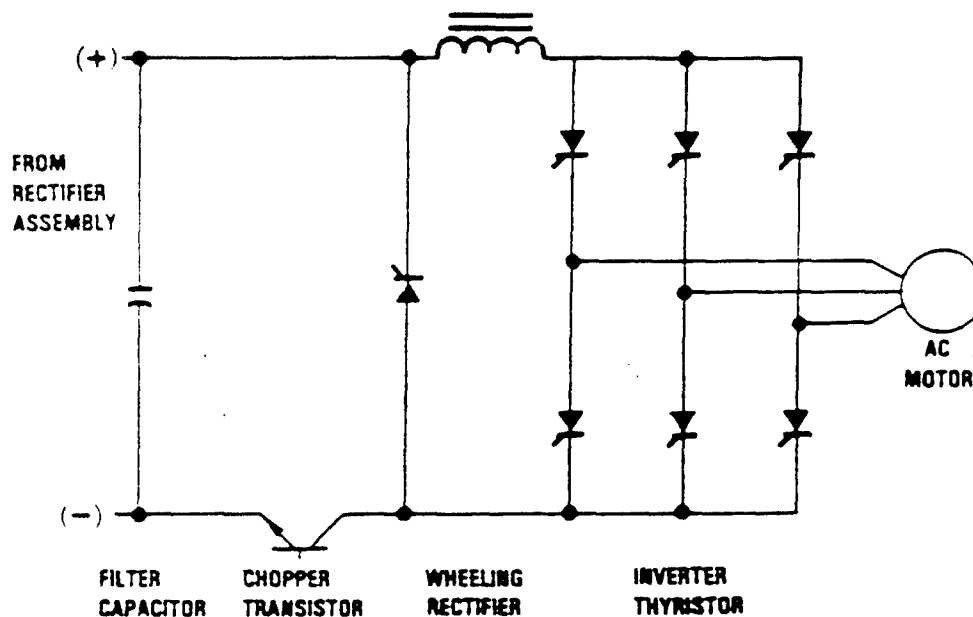


Figure 5.2-12. Chopper/Inverter Type PCU

Recently, potentially innovative electrical machines have been advanced by three different groups as candidates for vehicle electric drivetrain elements. These machines are: the DC homopolar machine, the AC homopolar machine, and the outside rotor PM synchronous machine.

Figure 5.2-13 shows an AC Drive 2 type PCU, the converter/inverter. It consists of a converter followed by a filter and a forced sequentially commutated inverter. The inverter output is applied to the AC motor. The converter section is basically a phase delay rectifier. It performs two primary functions: rectification of the input AC source (main alternator AC output) and regulation of the current to the inverter. The converter operation is bi-lateral, enabling it to receive and channel the reverse or regenerative power from the load (motor) to the input AC source (alternator).

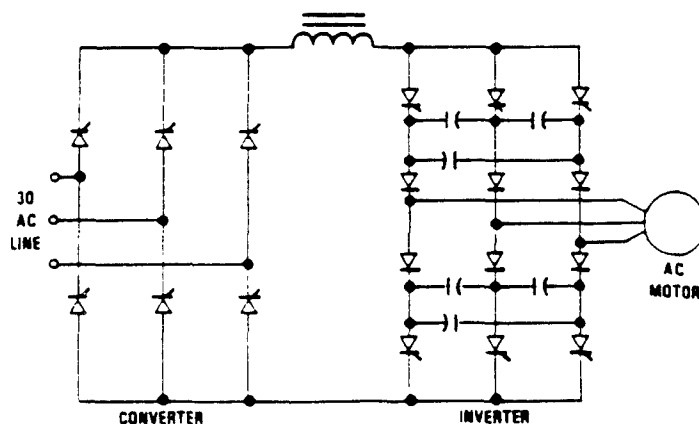


Figure 5.2-13. Converter/Inverter Type PCU

Each of the two PCU candidates (chopper/inverter and converter/inverter) can serve equally well in AC motor control applications. Included in this assessment is the consideration that both PCU types can operate bi-laterally, i.e., capable of allowing regenerative power feed-through from the load (motor) to the source (alternator). The selection basis is thus left to the comparison of physical and other miscellaneous characteristics. Weight and

volume tradeoffs between the two systems must be made for each vehicle configuration studied.

AC Drive 3 is similar to AC Drive 2 in that it uses an AC bus to transport the electrical traction power, but in place of the individual rectifier/inverter sets, line commutated cycloconverters are used. Also, the output frequency of the AC generator in Drive 3 must be high enough to enable efficient cycloconverter operation, at least three times the traction motor in current frequency. Disadvantages of cycloconverter drives are the need for a large number of power semiconductor devices per PCU and the poor power factor presented to the AC generator.

AC Drive 4 is the AC homopolar vehicle electric drive system presently under study at the University of Michigan. The unique feature of the drive is that it is the only AC drive system which does not employ traction power level PCUs. The frequency of the electrical power generated by the AC homopolar generators is the frequency of the generator's field excitation and is not a function of the prime mover/generator shaft speed. Speed control of the traction motors can be obtained without the use of power semiconductor devices that must pass the full power level of the traction motors. AC homopolar machines could be used as traction motors as well as generators, but the use of standard AC traction motors such as squirrel cage machines, eliminates the need for another set of field control oscillators and restricts the current collection support systems of homopolar machines to one location in the vehicle.

AC Drive 5 is a system that employs the innovative high power density outside rotor PM synchronous motors of Unique Mobility, Inc. of Englewood, Colorado. Two high frequency, shaft connected AC generators drive two traction motors through two semiconductor controlled rectifier (SCR) switching networks. The PM machines are of high phase order, typically eight phase, and thus the multiwire connections between the switching networks and the traction motors shown in the drive diagram. The SCR switching network shown can be augmented with a mechanical or electronic stator pole changing switching network that would provide for multiple speed/torque ranges and may eliminate the need for

mechanical gear shifting in the final drive. The SCR switching network is not to be confused with the PCUs of the more standard AC drives. This network simply directs the stator current to the correct windings in sync with the rotor position, it does not control the traction motor power. Power control of the traction motors is accomplished through field control of the AC generators. As in the DC and AC homopolar drive concepts, this system also passes the regenerative steering power exchange between the two tracks through all four electrical machines and the prime mover shaft.

5.2.3.3 Electronic Control

The Electronic Control Unit (ECU) is the primary unit for automatic control of the propulsion system and future electric power weapons systems. The ECU is responsible for controlling the system electrical parameters in response to operator command signals within the limitations of the system components. In addition, the ECU is responsible for detecting fault modes that may occur and initiating proper protective sequences. The ECU also provides status information for display to the operator.

A basic propulsion system control block diagram is shown in figure 5.2-14. This system can be expanded to handle advanced weaponry, such as, missile launchers, laser weapons, and electromagnetic (EM) weapons. Inherent in figure 5.2-14 is the Built in Test Equipment (BITE) capability for the system.

The general propulsion feedback control system of figure 5.2-14 was used as a basis for the study. The number of motors and PCUs can be decreased or increased depending on the configuration.

The ECU will be a microcomputer consisting of a microprocessor, memory, clock, and input/output (I/O) elements. Changes and growth of the control system can be accomplished more readily with a microcomputer than with dedicated circuitry. The microcomputer will communicate with the operator controls and displays, and the power system via a MIL-STD-1553 Bus. The microcomputer control system is shown in figure 5.2-15.

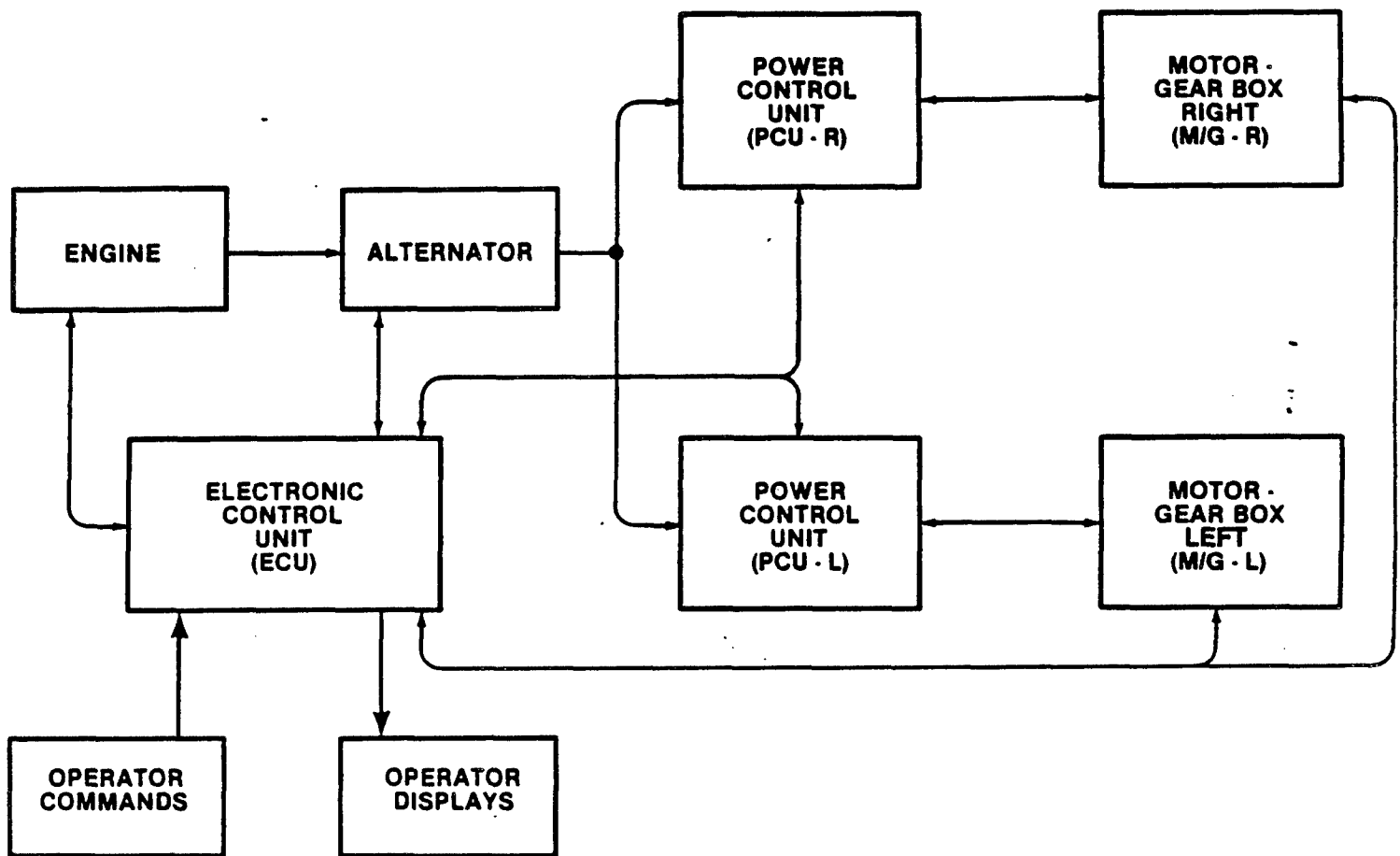


Figure 5.2-14. Electronic Control Concept for
Electric Propulsion System

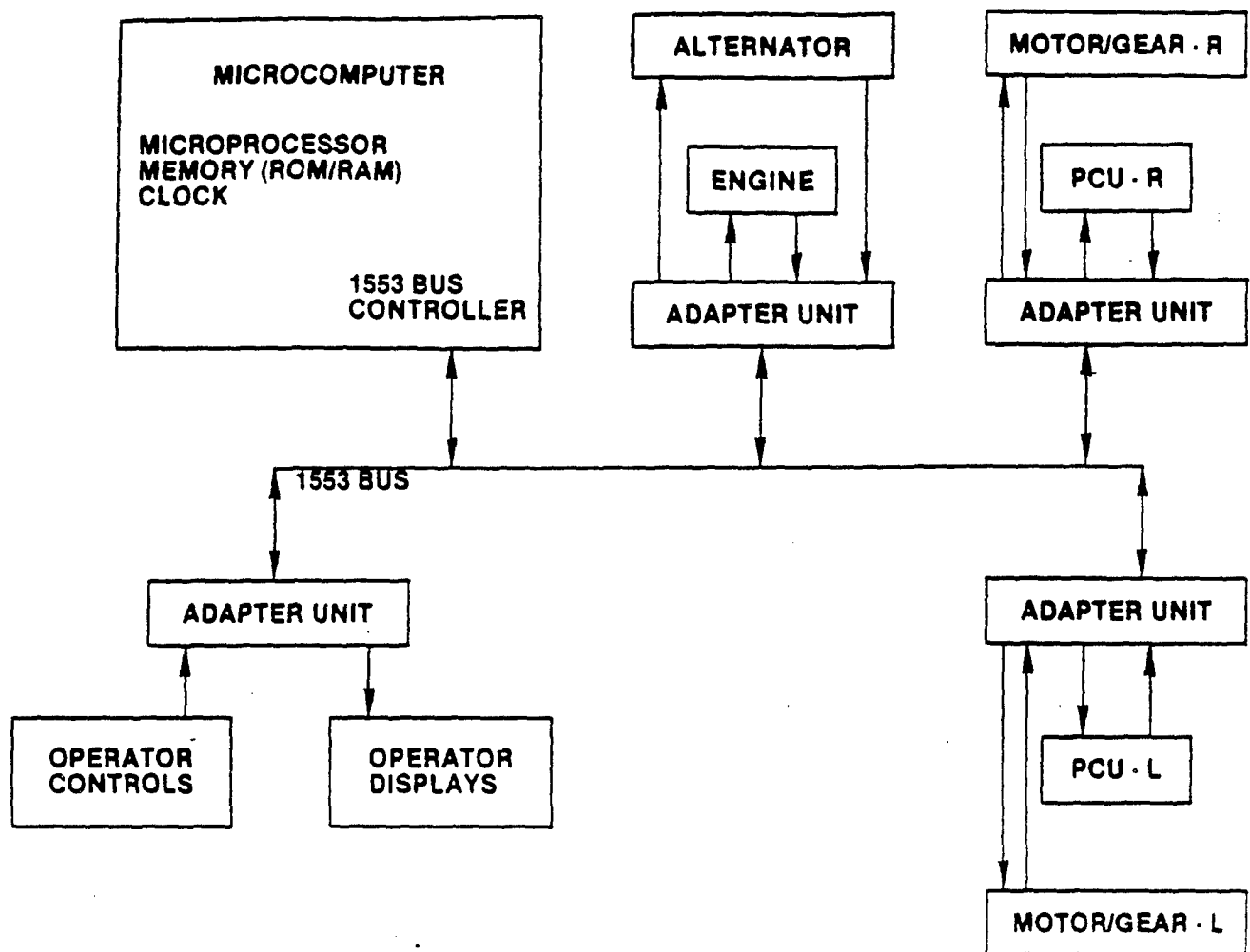


Figure 5.2-15. Microcomputer Control System

5.2.3.4 Brake Systems

The brake system must satisfy the performance requirements of the vehicle specification and provide the braking function by two separate mechanisms for redundancy during emergencies. The brake system concepts envisioned for the 19.5 and 40.0 ton electric drive concepts provide the brake function by a combination of mechanical and electric braking under microprocessor control. The mechanical brakes are hydraulically actuated wet disc brakes located on the transmission output shafts adjacent to the final drive. The electric braking is accomplished by coupling energy from the traction motors (acting in generator mode) back to the engine and to a resistance grid. The brake system weight and volume estimates used in the concept generation task are 110 pounds and 0.40 cubic feet for 19.5 ton concepts and 220 pounds and 0.80 cubic feet for 40 ton concepts. The brake system is defined in greater detail for the best three concepts in section 5.4.12.

5.2.3.5 Cooling System

The cooling system must provide adequate cooling for continuous operation at tractive effort equal to 0.7 GVW and 120°F ambient air temperature. Typically, the engine and transmission cooling systems are integrated in combat vehicles to minimize volume. However, for the candidate electric drive concepts, weight, and volume estimates for transmission cooling only were made. This was done to highlight the cooling requirement differences between the electric and mechanical drivetrains for the detailed analysis. The transmission cooling requirements for the electric drive were based on the average heat rejection of each concept. Average heat rejection was determined from the average transmission efficiency over a vehicle constant horsepower speed range of 5 to 45 miles per hour. For those electric drive concepts which are totally oil cooled, the data of figure 5.2-16 were based on estimates made for two reference transmission cooling systems, one for a 19.5 ton vehicle with heat rejection rate of 4200 btu per minute and one for a 40 ton vehicle with heat rejection rate of 8200 btu per minute. The reference cooling systems provide cooling for the generator, power conditioning

equipment, traction motors, and high speed gearboxes. Included in figure 5.2-16 are estimates for pumps, motors, valves, plumbing, oil reservoir, heat exchangers, and cooling fluid. Some concepts require a combination oil and air cooling system, notably concepts using air cooled traction motors. The weight and volume estimates for these concepts were determined by modifying the data of figure 5.2-16. The integrated cooling system for transmission and engine of the best three concepts is discussed in section 5.4.9.

5.2.3.6 Gear Systems

Mechanical gear systems are required for most candidate electric drive concepts at two locations: (1) a speed increaser gear set is required between the engine output and the generator input (called a transfer case) and (2) a single speed or two speed gearbox is required between the traction motor output and the final drive input. Also, concepts for Configuration II and III require gearboxes between the steer motor and the steer cross shaft and concepts for Configuration IV (dual path) require right angle and/or cross drive gearboxes. Gearbox weight and volume estimates used in developing candidate electric drive concepts are based on information from gearbox manufacturers or, where not available from GDLS gearbox analysis. The final drives, which in most cases have a 4:1 ratio, are not included as part of the electric transmission concepts. This is because the final drive is properly not considered to be part of a transmission. However, as the final drive is a subsystem of the vehicle propulsion system, it will be included in the analysis of the best three candidate systems (section 5.4).

5.2.4 Concept Descriptions.

A total of 38 concepts were generated utilizing electric drive components from Garrett Corporation, Westinghouse, ACEC, Unique Mobility, University of Michigan, and Jarret for the 19.5 and 40.0 ton vehicles. Concepts were developed for each of the four specified configurations in each weight category. The physical characteristics of each concept are presented in table B-1 through table B-38 of Appendix B. The total weight and volume of each candidate concept is presented along with average transmission efficiency for the vehicle speed range of 5 to 45 miles per hour. Final drive weight and volume estimates are not included in the transmission characteristics tables.

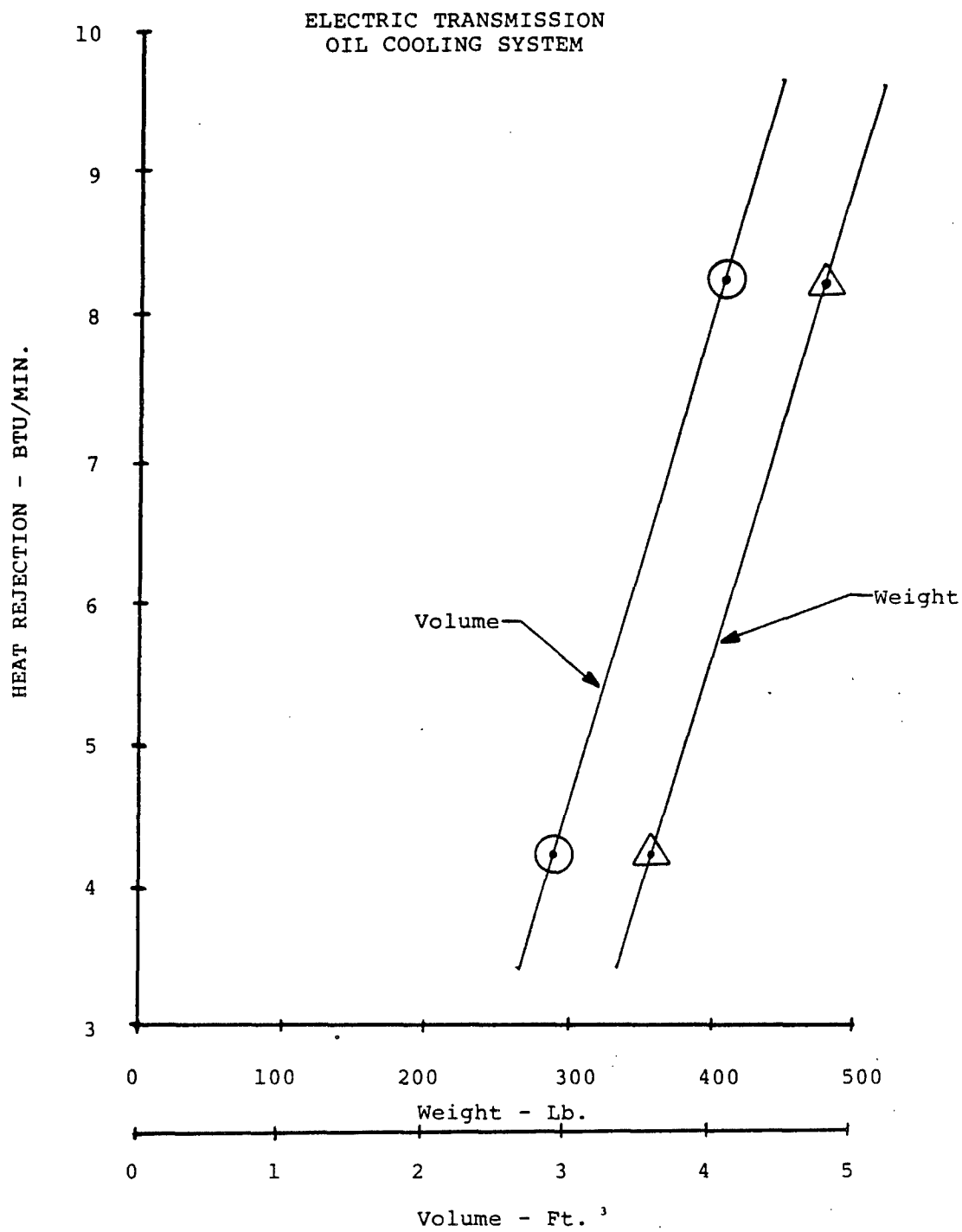


Figure 5.2-16. Electric Transmission Oil Cooling System Estimates

Three view drawings of selected transmissions concepts installed in the 19.5 ton vehicle and in the 40 ton vehicle are also presented in Appendix B. These layout drawings show space claims for the transmission concepts, the engine, air induction system, cooling system, and final drives. The Cummins VTA 903T engine is used in the 19.5 ton vehicle layout drawing and the AD1000 engine is shown in the 40 ton vehicle layouts. The VTA 903T and the AD1000 engine configurations shown in the layouts use a shallow oil pan. This is particularly advantageous to the 19.5 ton vehicle front engine installation where the available packaging height is limited. Also the after cooler on the VTA 903T engine was reconfigured for some installations to allow a more forward location of the engine. Effort has been made to package the power pack in a volume efficient manner and allow sufficient access space for maintenance. However, the power pack layouts are not considered to be optimum at this stage.

5.2.4.1 19.5 Ton Configuration I.

Concept I-1 consists of a Garrett rare earth cobalt PM synchronous motor and two speed reduction gearbox, at each drive sprocket. The Garrett rare earth cobalt PM synchronous generator supplies three phase power, conditioned by two DC link rectifier/inverter PCUs (one per motor). The generator, motors, gearboxes, and PCUs are all oil cooled. The concept has high volume attributed to the PCU which occupy 2.7 cubic feet each.

Concept I-2 consists of a Westinghouse induction motor cluster, comprised of (4) three phase induction motors mounted around a two speed reduction gearbox at each drive sprocket. The Westinghouse wound motor brushless generator supplies three phase power, conditioned by two DC link rectifier/inverter PCUs (one per motor cluster). The generator, motors, gearboxes, and PCUs are all oil cooled. The concept has high volume and low efficiency attributed to the PCUs and traction motors.

Concept I-3 consists of a Westinghouse PM motor cluster, comprised of four PM synchronous DC motors mounted around a two speed reduction gearbox, at each drive sprocket. The Westinghouse wound rotor brushless generator supplies three phase power, rectified by two DC link PCUs (one per motor cluster). The generator, motors gearboxes, and PCUs are all oil cooled. The concept has high volume and low efficiency attributed to the PCUs.

Concept I-4 consists of an ACEC separately excited DC traction motor and two speed reduction gearbox, at each drive sprocket. The ACEC three phase AC generator with built-in brushless exciter and power rectifier supplies DC power to the traction motors without any external PCUs. The generator and motors are all air cooled. The concept has virtually no technical risk due to the generator and motors, which are designed from production models. High volume and weight are attributed to the generator and traction motors.

Concept I-5 consists of an ACEC, separately excited DC traction motor, and two speed reduction gearbox, at each drive sprocket. Excitation of the motors is controlled by the ECU. The Garrett rare earth cobalt PM generator supplies three phase power which is rectified to DC. The generator, rectifier, and gearboxes are oil cooled and the traction motors are air cooled. The concept has low volume and high efficiency due to the generator, rectifier combination used

Concept I-6 consists of two Garrett rare earth cobalt PM traction motors (a high torque and a high speed motor) that are combined by a planetary gearbox at each drive sprocket. The motor combination eliminates the need for a two speed gearbox. A Garrett rare earth cobalt PM generator supplies three phase power, conditioned by six control converters. The generator, motors, gearboxes, and PCUs are all oil cooled. The concept has high weight and volume due to the two traction motors at each drive sprocket.

Concept I-7 consists of a Westinghouse separately excited DC homopolar traction motor and single speed reduction gearbox, at each drive sprocket. A Westinghouse separately excited DC homopolar generator supplies DC power directly to the traction motors. Excitation power for the motors and generator is supplied by a separate engine driven PM generator. The generators, motors, and gearboxes are all oil cooled. High efficiency is achieved due to no required conditioning of the generated DC power. High weight and technical risk are attributed to the generator and motors, which are at an early developmental stage.

Concept I-8 consists of two University of Michigan AC homopolar generators which supply AC power directly to two Westinghouse induction motor clusters, comprised of four induction motors mounted around a two speed gearbox. The

generator, motors, and gearboxes are all oil cooled. The concept has high weight attributed to the generators and traction motor clusters. High technical risk and low reliability are attributed to the homopolar generator, which utilizes a liquid metal current collection system.

Concept I-9 consists of a Unique Mobility neodymium PM self-synchronous motor and single speed reduction gearbox, at each drive sprocket. The Garrett PM generator supplies three phase power, conditioned by a rectifier in series with an inverter motor controller. The generator, rectifier, motor controllers, and gearboxes are oil cooled. The traction motors are air cooled. The concept has low volume and weight attributed to the generator and traction motors. High efficiency is achieved through the traction motors that have an efficiency rating of 96 percent. However, there is a high technical risk due to the early developmental state of the self-synchronous motors.

Concept I-10 consists of a Garrett rare earth cobalt PM traction motor and two speed reduction gearbox, at each drive sprocket. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by three control converters. The concept is a revision of concept I-1, the difference being the replacement of the large, heavy PCUs. The results of the change are a reduction in volume and slight increase of efficiency.

5.2.4.2 19.5 Ton Configuration IA.

Concept 1A-1 consists of a Garrett rare earth PM traction motor and two speed reduction gearbox, mounted inside each of four vehicle drive sprockets. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by four DC link rectifier/inverter PCUs (one per motor). The generator, motors, reduction gearboxes, and PCUs are all oil cooled. The motor and gearbox mounting results in a substantial decrease of in-hull volume. The concept has high weight due to the traction motors and PCUs.

Concept 1A-2 consists of a Jarret variable reluctance traction motor directly driving each of four drive sprockets. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by four controllers (one per

motor). The traction motors and controllers are air cooled and the generator is oil cooled. The concept has high volume and weight attributed to the traction motors.

Concept 1A-3 consists of a Jarret variable reluctance motor and final drive reduction gearbox at each of four drive sprockets. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by four controllers (one per motor). The traction motors, and controllers are air cooled and the generator and gearboxes are oil cooled. The concept has good efficiency attributed to the traction motors and the motor controllers.

5.2.4.3 19.5 Ton Configuration II

Concept II-1 consists of a Garrett rare earth cobalt PM traction motor and two speed reduction gearbox, driving the propulsion cross shaft. A similar Garrett PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. The Garrett rare cobalt PM generator supplies three phase power conditioned by DC link rectifier/inverter PCUs to the propulsion and the steer motors. The generator, traction and steer motor, reduction gearboxes, and PCUs are all oil cooled.

Concept II-2 consists of a Westinghouse PM cluster, comprised of four PM synchronous DC traction motors mounted around a two speed reduction gearbox that drives the propulsion cross shaft. A Garrett PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. The Westinghouse wound rotor brushless generator supplies three phase power, conditioned by DC link rectifier/inverter PCUs, to the propulsion and steer motors. The generator, traction motors, reduction gearboxes, and PCUs are all oil cooled. The concept has low efficiency due to PCU and traction motor efficiencies.

Concept II-3 consists of an ACEC separately excited DC traction motor and two speed reduction gearbox driving the propulsion shaft. Excitation of the motor is controlled by the ECU. A Garrett PM steer motor and single reduction gearbox control the steer cross shaft to provide vehicle steering. The

Garrett rare earth cobalt PM generator supplies three phase power which is rectified to DC. The generator, steer motor, reduction gearboxes, and PCUs are oil cooled and the propulsion motor is air cooled. The concept has high weight attributed to the DC traction motor.

Concept II-4 consists of a Westinghouse separately excited DC homopolar traction motor and single speed reduction gearbox driving the propulsion shaft. A Garrett PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. Excitation for the homopolar generator and motors is provided by an engine driven PM generator which also supplies power to the steer motor through a DC link PCU. The generators, traction motors, reduction gearboxes, and PCUs are all oil cooled. The concept has very high efficiency but also has high weight due to the propulsion motor.

Concept II-5 consists of a Westinghouse induction motor cluster, comprised of four induction motors mounted around a two speed reduction gearbox that drives the propulsion cross shaft. A Garrett PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. The University of Michigan homopolar generator supplies three phase power to the induction motor cluster and to the steer motor. The generator, motors, reduction gearboxes, and PCU are all oil cooled. The concept has high technical risk due to the homopolar generator.

Concept II-6 consists of a Unique Mobility neodymium PM traction motor and single speed reduction gearbox that drives the propulsion cross shaft. A PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by a rectifier in series with the motor controllers. The generator, reduction gear boxes, rectifier, and motor controllers are oil cooled, and the propulsion motor cluster and steer motor are air cooled. The concept has high efficiency and low weight due to the propulsion motor.

5.2.4.4 19.5 Ton Configuration III

Concept III-1 consists of a Garret rare earth cobalt PM traction motor and two speed reduction gearbox, at each drive sprocket. A Garrett PM steer motor and a single speed reduction gearbox drive the steer cross shaft. The Garrett rare earth cobalt PM generator supplies three phase power to the propulsion and steer motors. The generator, motors, reduction gearboxes, and PCUs are all oil cooled.

Concept III-2 consists of an ACEC separately excited DC traction motor and a two speed reduction gearbox, at each drive sprocket. Excitation of the motor is controlled by the ECU. A Garrett PM steer motor and a single speed reduction gearbox drive the steer shaft. The Garrett rare earth cobalt PM generator supplies three phase power, which is rectified to DC for the propulsion motors and for the DC link inverter for the steer motor. The generator, steer motor, reduction gearboxes, and PCU are oil cooled and the propulsion motors are air cooled. The concept has high efficiency and low volume, due to the generator and rectifier combination.

Concept III-3 consists of a Unique Mobility neodymium PM self-synchronous traction motor and a single speed reduction gearbox, at each drive sprocket. A PM steer motor and a single speed reduction gearbox drive the steer shaft. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by a rectifier in series with two motor controllers (one per motor) for the propulsion motors and one controller for the steer motor. The generator, reduction gearboxes, rectifier, and PCUs are oil cooled and the propulsion motors and steer motor are air cooled. The concept has low volume and weight and high efficiency attributed to the propulsion motors and generator.

5.2.4.5 19.5 Ton Configuration IV

Concept IV-1 consists of a Garrett rare earth cobalt PM traction motor and two speed gearbox, at each drive sprocket. A combining planetary sums the power from the engine and traction motors at the sprocket. A Garrett rare earth

cobalt PM generator supplies three phase power, conditioned by two DC link rectifier/inverter PCUs (one per motor). The generator, traction motors, reduction gearboxes, and PCUs are all oil cooled.

Concept IV-2 consists of a Unique Mobility neodymium PM self-synchronous motor at each drive sprocket. A combining planetary gear set sums the power from the engine and traction motors at the drive sprocket. A Garrett rare earth cobalt PM generator supplies three phase power, conditioned by a rectifier in series with two inverter motor controllers (one per motor). The generator, reduction gearboxes, rectifier, and motor controllers are oil cooled and the traction motors are air cooled. The concept has low volume and weight and high efficiency due to the traction motors and generator.

Concept IV-3 consists of an ACEC separately excited DC traction motor and two speed gearbox at each drive sprocket. Excitation of the motors is controlled by the ECU. A combining planetary gear set sums the power from the engine and traction motors at the drive sprockets. A Garrett rare earth cobalt PM generator supplies three phase power which is rectified to DC for the traction motors. The generator, reduction gearboxes, and rectifier are oil cooled and the traction motors are air cooled. The concept has low volume and high efficiency attributed to the generator and rectifier combination.

Concept III-3 consists of a Unique Mobility neodymium PM self-synchronous traction motor and a single speed reduction gearbox, at each drive sprocket. A PM steer motor and a single speed reduction gearbox drive the steer shaft. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by a rectifier in series with two motor controllers (one per motor) for the propulsion motors and one controller for the steer motor. The generator, reduction gearboxes, rectifier, and PCUs are oil cooled and the propulsion motors and steer motor are air cooled. The concept has low volume and weight and high efficiency attributed to the propulsion motors and generator.

5.2.4.5 19.5 Ton Configuration IV

Concept IV-1 consists of a Garrett rare earth cobalt PM traction motor and two speed gearbox, at each drive sprocket. A combining planetary sums the power

from the engine and traction motors at the sprocket. A Garrett rare earth cobalt PM generator supplies three phase power, conditioned by two DC link rectifier/inverter PCUs (one per motor). The generator, traction motors, reduction gearboxes, and PCUs are all oil cooled.

Concept IV-2 consists of a Unique Mobility neodymium PM self-synchronous motor at each drive sprocket. A combining planetary gear set sums the power from the engine and traction motors at the drive sprocket. A Garrett rare earth cobalt PM generator supplies three phase power, conditioned by a rectifier in series with two inverter motor controllers (one per motor). The generator, reduction gearboxes, rectifier, and motor controllers are oil cooled and the traction motors are air cooled. The concept has low volume and weight and high efficiency due to the traction motors and generator.

Concept IV-3 consists of an ACEC separately excited DC traction motor and a two speed gearbox at each drive sprocket. Excitation of the motors is controlled by the ECU. A combining planetary gear set sums the power from the engine and traction motors at the drive sprockets. A Garrett rare earth cobalt PM generator supplies three phase power which is rectified to DC for the traction motors. The generator, reduction gearboxes, and rectifier are oil cooled and the traction motors are air cooled. The concept has low volume and high efficiency attributed to the generator and rectifier combination.

5.2.4.6 40 Ton Configuration I

Concept I-1 consists of a Garrett rare earth cobalt PM synchronous motor and two speed reduction gearbox at each drive sprocket. The Garrett rare earth cobalt PM synchronous generator supplies three phase power, conditioned by two DC link rectifier/inverter PCUs (one per motor). The generator, motors, gearboxes, and PCUs are all oil cooled. The concept has high weight attributed to the PCUs and traction motors.

Concept I-2 consists of an ACEC separately excited DC traction motor and two speed reduction gearbox, at each drive sprocket. Excitation of the motors is controlled by the ECU. The Garrett rare earth cobalt PM generator supplies

three phase power which is rectified to DC. The generator, rectifier, and gearboxes are oil cooled and the traction motors are air cooled. The concept has high efficiency due to the generator, rectifier combination used, but also, has high weight attributed to the traction motors.

Concept I-3 consists of a Garrett rare earth cobalt PM traction motor and two speed reduction gearbox, at each drive sprocket. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by three control converters. The concept is a revision of concept I-1, the difference being the replacement of the large, heavy PCUs. The results of the change are a reduction in volume and slight increase of efficiency.

Concept I-4 consists of a Westinghouse separately excited DC homopolar traction motor and single speed reduction gearbox, at each drive sprocket. A Westinghouse separately excited DC homopolar generator supplies DC power directly to the traction motors. Excitation of the motors and generator is provided by a separate engine driven AC generator. The generators, motors, and gearboxes are all oil cooled. High efficiency is achieved because no conditioning of the generated DC power is required. High weight and technical risk are attributed to the generator and motors, which are at an early developmental stage.

Concept I-5 consists of two University of Michigan AC homopolar generators which supply AC power directly to a Westinghouse induction motor cluster, comprised of four induction motors mounted around a two speed gearbox at each drive sprocket. The generator, motors, and gearboxes are all oil cooled. The concept has high weight attributed to the generators and traction motor clusters. High technical risk is attributed to the homopolar generator, which utilizes a liquid metal current collection system.

Concept I-6 consists of a Unique Mobility neodymium PM self-synchronous motor and single speed reduction gearbox, at each drive sprocket. The Garrett PM generator supplies three phase power, conditioned by a rectifier in series with two motor controllers. The generator, rectifier, motor controllers, and gearboxes are oil cooled. The traction motors are air cooled. The concept

has low volume and weight attributed to the generator and traction motors. High efficiency is achieved through the traction motors that have an efficiency rating of 96 percent. However, there is a high technical risk due to the early developmental state of the self-synchronous motors.

5.2.4.7 40 Ton Configuration II

Concept II-1 consists of a Westinghouse separately excited DC homopolar traction motor and single speed reduction gearbox driving the propulsion shaft. A PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. Excitation for the homopolar generator and motors is provided by an engine driven AC generator which also provides power to the PM steer motor through a DC link controller. The generator, traction motors, reduction gearboxes, and PCUs are all oil cooled. The concept has very high efficiency but also has high weight due to the propulsion motor.

Concept II-2 consists of a Westinghouse induction motor cluster, comprised of four induction motors mounted around a two speed reduction gearbox. A PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. The University of Michigan AC homopolar generator supplies three phase power to the induction motor cluster and to a DC link rectifier/inverter PCU for the steer motor. The generator, motors, reduction gearboxes, and PCU are all oil cooled. The concept has a high technical risk due to the homopolar generator.

Concept II-3 consists of a Westinghouse PM cluster, comprised of four PM synchronous AC traction motors mounted around a two speed reduction gearbox. A PM steer motor and single speed reduction gearbox control the steer cross shaft to provide vehicle steering. The Westinghouse wound rotor brushless generator supplies three phase power, conditioned by DC link rectifier/inverter PCUs, to the propulsion and steer motors. The generator, traction motors, reduction gearboxes, and PCUs are all oil cooled. The concept has low efficiency and high volume due to the PCUs.

Concept II-4 consists of a Unique Mobility neodymium PM traction motor cluster (three motors) and a single speed reduction gearbox. A PM steer motor with single speed reduction gearbox drives the steer cross shaft thus providing vehicle steering. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by a rectifier in series with the motor controllers. The generator, reduction gearboxes, rectifier, and PCUs are oil cooled, and the propulsion motor cluster and steer motor are air cooled. The concept has high efficiency and low weight due to the propulsion motor cluster.

5.2.4.8 40 Ton Configuration III

Concept III-1 consists of a Garrett rare earth cobalt PM traction motor and two speed reduction gearbox, at each drive sprocket. A Garrett PM steer motor and a single speed reduction gearbox drive the steer shaft. The Garrett rare earth cobalt PM generator supplies three phase power, conditioned by DC link rectifier/inverter PCUs, to the propulsion and steer motors. The generator, motors, reduction gearboxes, and PCUs are all oil cooled. The concept has low efficiency attributed to the traction motors.

5.2.4.9 40 Ton Configuration IV

Concept IV-1 consists of a Garrett rare earth cobalt PM traction motor and two speed gearbox, at each drive sprocket. A Combining planetary gear set sums the power from the engine and traction motors at the sprocket. A Garrett rare earth cobalt PM generator supplies three phase power, conditioned by DC link PCUs to the propulsion motors. The generator, traction motors, reduction gearboxes, and PCUs are all oil cooled. The concept has good efficiency and low volume due to the generator and traction motors.

Concept IV-2 consists of a Unique Mobility neodymium PM self-synchronous motor cluster (two motors) at each drive sprocket. A combine planetary gear set sums the power from the engine and traction motors at the drive sprocket. A Garrett rare earth cobalt generator supplies three phase power, conditioned by a rectifier in series with four motor controllers (one per motor). The generator, reduction gearboxes, rectifier, and motor controllers are oil

cooled and the traction motors are air cooled. The concept has low volume and weight and high efficiency due to the traction motors.

5.3 CONCEPT SCREENING/METHODOLOGY AND BEST THREE CONCEPTS

In this section, the electric drivetrain concept screening methodology which lead to the selection of the best three candidates is discussed. The factors and utility functions which comprise the screening methodology are explained. The results of the evaluation, the concept scores, and the best three candidates are presented in sections 5.3.4 and 5.3.5.

5.3.1 Screening Methodology and Scoring Rationale

For screening the electric drivetrain concepts, GDLS developed a scoring system which numerically rated each concept, with the best concepts receiving the highest scores. The scoring incorporates the contract specified screening factors of performance, volume, technical risk, weight, reliability, and safety. Weight factors were assigned to each screening factor according to contract priority ranking and the consensus of the GDLS team members. Utility functions were developed for each screening factor with utility ranging from a low merit of 0 to a high merit of 10.

Therefore concept scoring is computed as follows. Concept subscores in each screening factor category were obtained from the product of the utility score and the category weight factor. The concept total score is the sum of its subscores from each of the six categories. With the weight factors totaling 100 and maximum utility scores of 10, the best total score obtainable is 1000 points. Since the screening methodology yields a numerical score for each candidate electric drive concept, the three best concepts are those with the highest scores.

The best three concepts selected are the highest scoring concepts from all 19.5 and 40.0 ton candidates. As required by the contract, two of the best three concepts apply to both the 19.5 ton and 40.0 ton vehicles. The screening methodology stems from the GDLS team's desire for a systematic

evaluation process to screen a large number of concepts and maintain a high degree of consistency.

5.3.2 Screening and Weight Factors

The contract specified screening factors used in concept screening, in their order of priority, are performance, volume, technical risk, weight, reliability, and safety. These screening factors were assigned weight factors to be used in the GDLS scoring system which appear in table 5.3-1.

Performance, which relates directly to vehicle mobility and has a major impact on survivability was assigned a weight factor of 32. Concept performance was divided into power available at the sprocket, regenerative efficiency, and skid-out capability.

TABLE 5.3-1. SCREENING FACTORS

<u>RANK</u>	<u>SCREENING FACTOR</u>	<u>WEIGHT FACTOR</u>
1	Performance	32
2	Volume and Space Utilization	21
3	Technical Risk	16
4	Weight	13
5	Reliability and Maintainability	10
6	Safety	<u>8</u>
		100 Total

Power available at the sprocket was given a weight factor of 17. It was determined to be the most important aspect of performance by the GDLS team. Power at the sprocket varies in each concept depending on the system efficiencies. Vehicle acceleration, maximum speed, and gradability are all dependent on power at the sprocket.

Regenerative efficiency was assigned a weight factor of 9 due to its effects on vehicle steer capability. Regeneration is the concept's ability to transfer power from the inside track to the outside track while negotiating a turn. Regeneration is essential for the vehicle to possess optimum steer capability, which as a goal is the ability to achieve skid out over its speed range. In addition, overall fuel efficiency is dependent on regeneration efficiency since all power regenerated reduces the power required from the engine during steer conditions.

Skid out capability is a concept's ability to achieve a 0.7g skid-out turn over the 5 to 45 mph speed range. Concepts with high skid-out capability have the ability to turn at minimum radius over the speed range. However, skid-out will seldom be required in a drive cycle which is why regeneration efficiency was assigned a higher weight factor.

System volume and space utilization is ranked second in priority and was assigned a weight factor of 21. Reduction of the drivetrain installed volume will result in improved survivability of the vehicle system because of reduced vehicle size/lower silhouette and/or increased payload. The design flexibility and modularity of electric drive concepts are evaluated to determine impact on space utilization.

Technical risk, ranked third in priority, was assigned a weight factor of 16. This was seen as being an important factor since many electric drive concepts involve new technologies that are in early developmental stages. A concept with high technical risk may encounter unforeseen problems during development and never meet predetermined design standards.

Weight was given a weight factor of 13 since it was ranked fourth in priority and was not taken to be as critical a factor as volume or technical risk. Most of the electric drive concepts have weights which are minimal when compared to the overall vehicle weight. However, the system weight will affect the performance of the vehicle in acceleration and steering. Furthermore, weight could be a factor in the 19.5 ton vehicle if swim capability is desired.

Reliability and maintainability, which was ranked fifth in priority, was assigned a weight factor of ten. The long life of electric motors and generators, usually 10,000 hours or more, should be an advantage of electric drive over mechanical drive, in the area of reliability. Reliability and maintainability was evaluated by examining drivetrain failure and the time to repair failure.

Ranked last in priority, safety was given a weight factor of 8. Safety was evaluated in terms of crew safety. Some safety concerns were fire hazard and toxicity of some materials.

5.3.3 Utility Functions

Utility functions were generated for each screening factor in an effort to assess concept utility in each of the scoring categories. Utility scores ranged from 0 to 10, with 10 indicating the highest utility. The range of the parameter scale was generally determined from the data collected for each screening factor. The shape of each utility function was based on the engineering judgement and experience of the GDLS team. The utility functions that were used in the assessment of candidate concepts are presented and discussed in the following paragraphs.

Performance: Performance is subdivided into three categories:

- o Power at the Sprocket
- o Regeneration Efficiency
- o Skid-out Capability

Power Available at the Sprocket: Constant horsepower available at the sprocket was assessed in the following manner. The contract required constant power at the sprocket to be 365 Hp in the 19.5 ton vehicle and 730 Hp in the 40.0 ton vehicle; therefore, concepts meeting the required power were given a utility score of 10. The GDLS team felt that the concepts should closely match the required power output to meet the desired performance characteristics.

POWER AT THE SPROCKET (W.F. = 17)

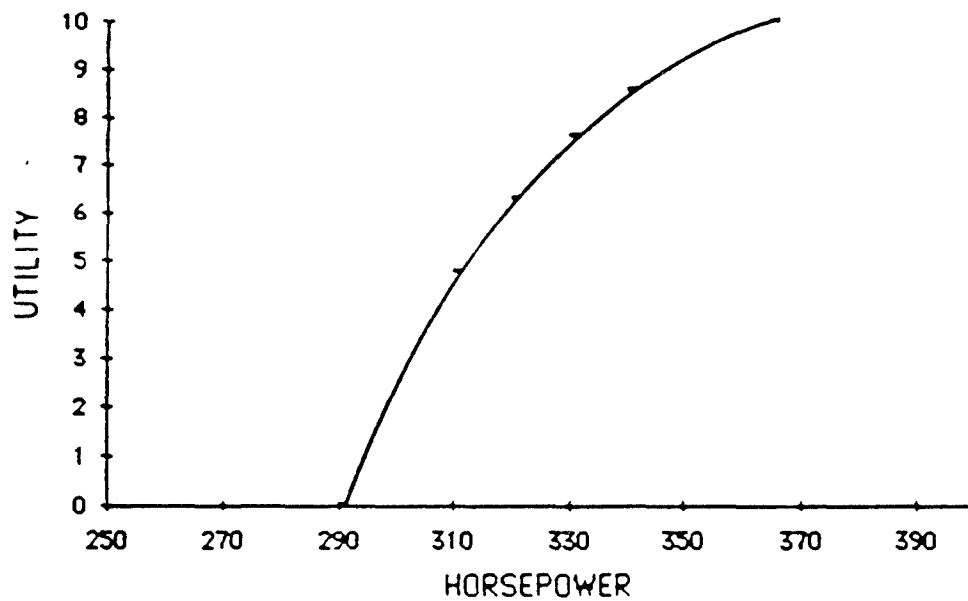


Figure 5.3-1. Utility Function for Sprocket Power, 19.5 Ton Vehicle

As a result, the utility curve drops sharply to zero at 290 Hp for the 19.5 ton vehicle and 630 Hp for the 40.0 ton vehicle. Figure 5.3-1 shows the utility of horsepower available at the sprocket for the 19.5 ton vehicle and figure 5.3-2 shows the utility of horsepower available for the 40 ton vehicle.

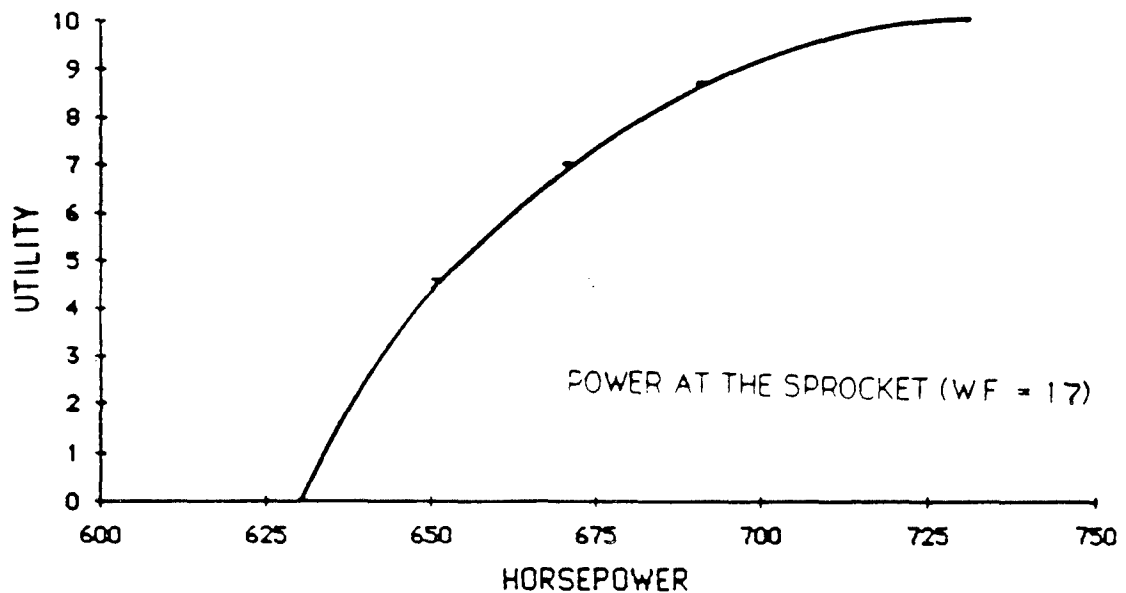


Figure 5.3-2. Utility Function for Sprocket Power, 40.0 Ton Vehicle

Regenerative Efficiency: The analysis of regenerative efficiency resulted in the curve which yields a utility score of 10 for 90% efficiency and rapidly drops to zero for 50% efficiency. The best concepts possess regenerative efficiencies close to 90% which was the basis for the upper end of the curve. In order to obtain the minimum acceptable steering characteristics, it was determined that concepts regenerative efficiency should be above 70%. For this reason, the curve drops very rapidly below 70% to the minimum score of zero for 50%. The utility of regenerative efficiency during steer for the 19.5 ton and 40.0 ton vehicles is shown in figure 5.3-3.

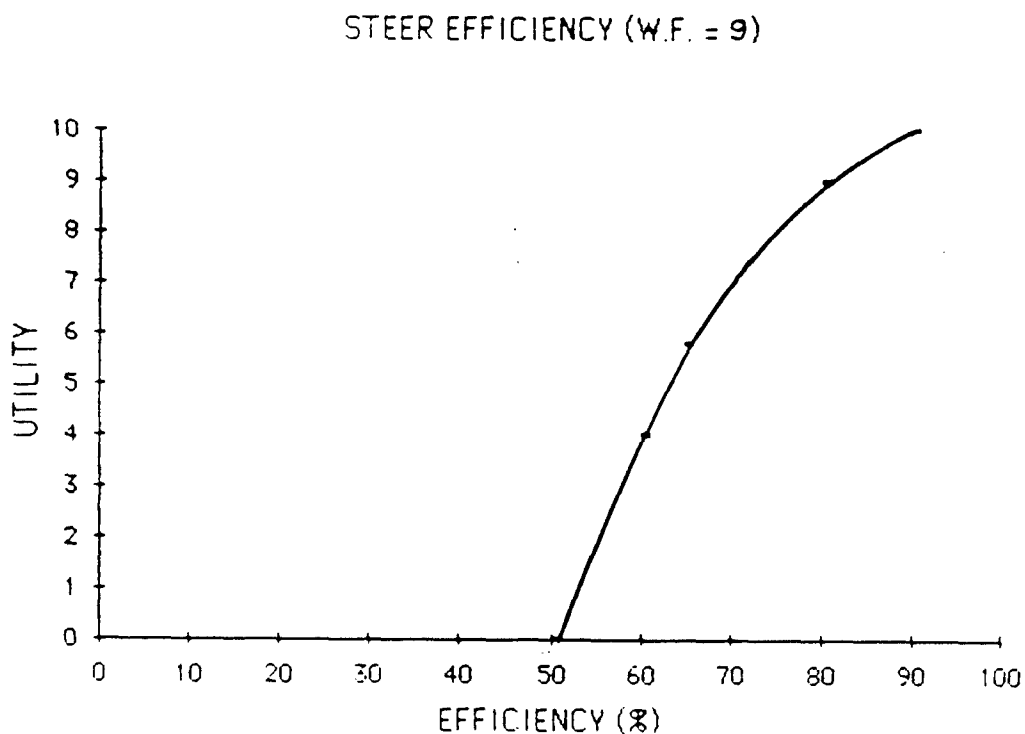


Figure 5.3-3. Utility Function for Regenerative Efficiency

Skid-out Capability: Skid-out capability is a measure of the concept's ability to achieve a .7g turn over the vehicle speed range. The ratio of the concept ability to turn relative to the maximum theoretical 0.7g turn is the parameter used to determine utility. For example, if a concept can achieve the .7g turn over the vehicle speed range then the turn ratio is 1.0 and utility is 10. However, if the maximum turn a concept can achieve is 0.35g then the turn ratio is 0.5 and utility is zero. The utility curve for skid-out capability is presented in figure 5.3-4 for the 19.5 and 40.0 ton vehicle concepts.

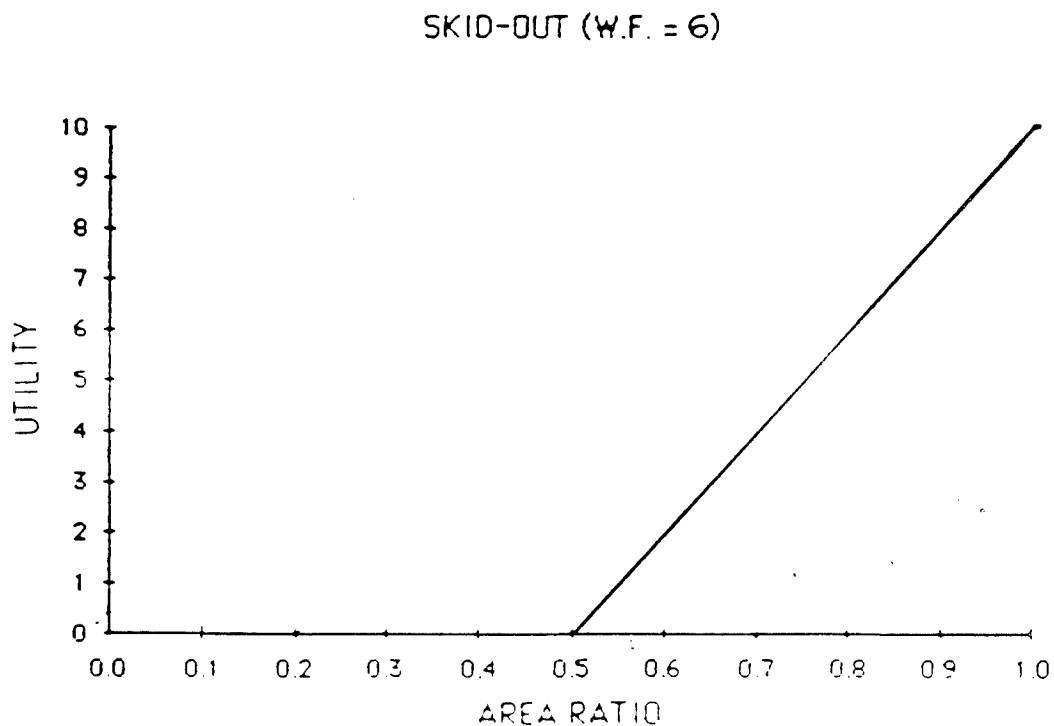


Figure 5.3-4. Utility Function for Skid-Out Capability

Volume and Space Utilization: System installed volume and space utilization were assessed for each concept based on the individual transmission concept volumes and the power pack layout drawings of Appendix B. A linear utility function was developed for each vehicle weight category based on the installed electric transmission volume with point deductions for various levels of space utilization. The utility-volume function for the 19.5 ton electric drive concepts yield a maximum utility of 10 for an installed volume of 12 cubic feet and zero utility at 25 cubic feet, while for the 40 ton concepts an installed volume of 17 cubic feet yields a utility of 10 and a volume of 30 cubic feet yields zero utility. The lowest installed volume determined from all concepts in each vehicle weight category was used to establish the maximum utility points. The utility functions for volume are given by figures 5.3-5 and 5.3-6 for the 19.5 and 40.0 ton concepts. Once a utility value for the installed volume of an individual concept was determined it was adjusted for space utilization. These adjustments are the same for both weight categories and are in the form of deductions to the initial utility determination. The space utilization deductions are made as follows:

- o No deduction for Configurations I Concepts
- o 1 point deduction for Configuration III Concepts due to one mechanical cross shaft which reduces design flexibility and space utilization.
- o 2 point deduction for Configuration II and Configuration IV Concepts due to two mechanical cross shafts (Configuration II) or one cross shaft and a longitudinal engine connect shaft (Configuration IV) which further reduces design flexibility and space utilization.

Technical Risk: Utility scores were individual assigned to concepts depending on the developmental state of the components utilized. The highest technical risk component of each concept was the determining factor in that concept's utility score. Figure 5.3-7 show the utility curve of technical risk for the 19.5 and 40.0 ton vehicles.

The ACEC DC machinery was given a score of ten since their designs are modifications of existing production machinery and are low risk. Garrett and

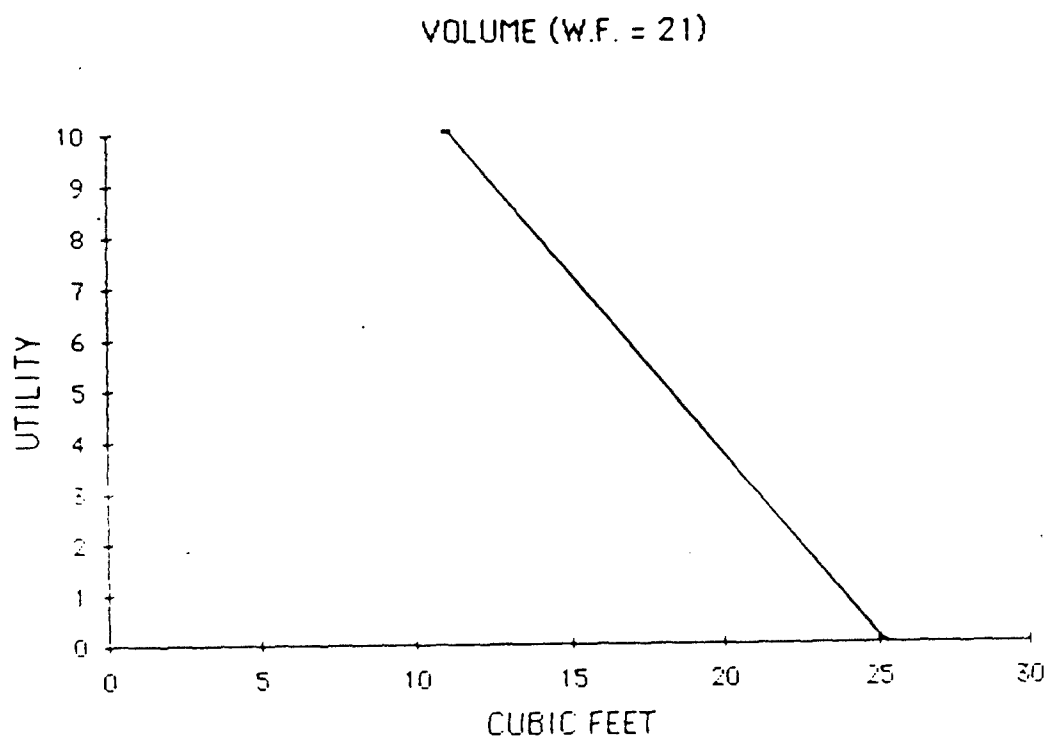


Figure 5.3-5. Utility Function for Volume, 19.5 Ton Vehicle

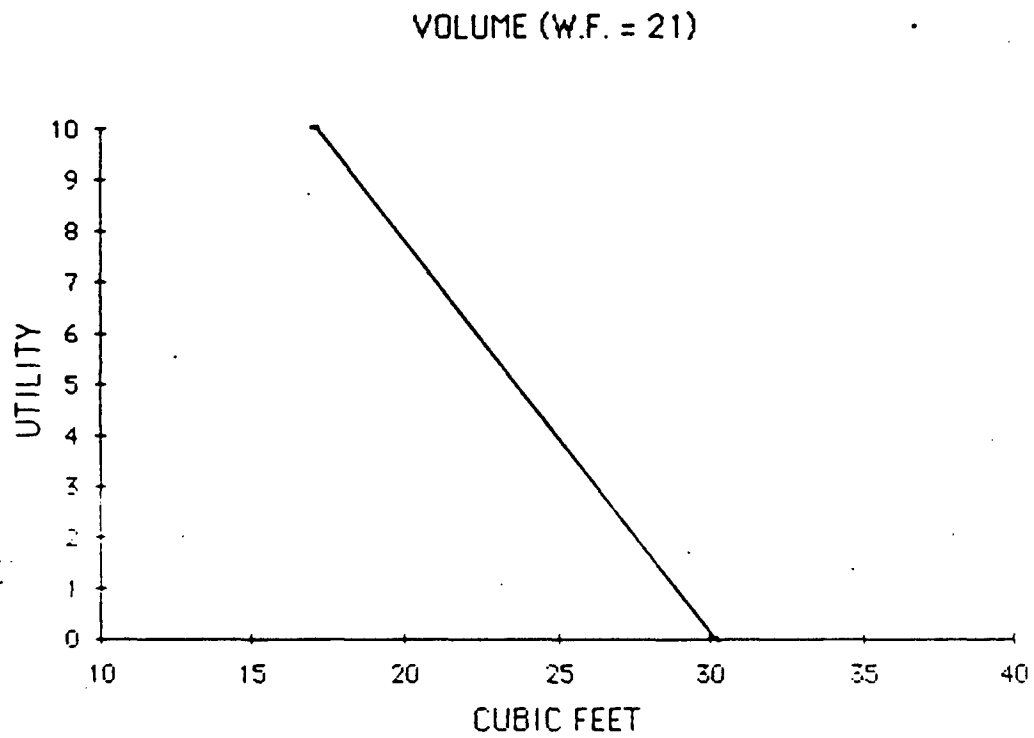


Figure 5.3-6. Utility Function for Volume, 40.0 Ton Vehicle

Westinghouse machinery are in the initial stage of development and are medium risk, so their score is lowered to seven points. The highest risk machinery in our concepts are the Unique Mobility PM Motor, and the AC and DC homopolar machinery. These components are presently concept "paper" designs with some prototype hardware being built at this time, which makes them a high risk. In addition to the previously discussed scores, a two point deduction was taken from any concept with a two speed gearbox at each drive sprocket. This stems from the concern of simultaneously shifting two individual gearboxes.

Weight: Concept weight was scored with a linear function yielding the maximum score for the lightest and minimum score for the heaviest concepts. More specifically, a high score of ten was given for a weight of 1,200 lbs (19.5 ton) and 2,200 lbs (40.0 ton) and the low score of zero for concepts of 3,000 lbs (19.5 ton) and 4,500 lbs (40.0 ton vehicle). Therefore, the weight curve represents a straight forward comparison of the concepts. These linear utility function curves are shown in figures 5.3-8 and 5.3-9 for the 19.5 and 40.0 ton vehicles respectively.

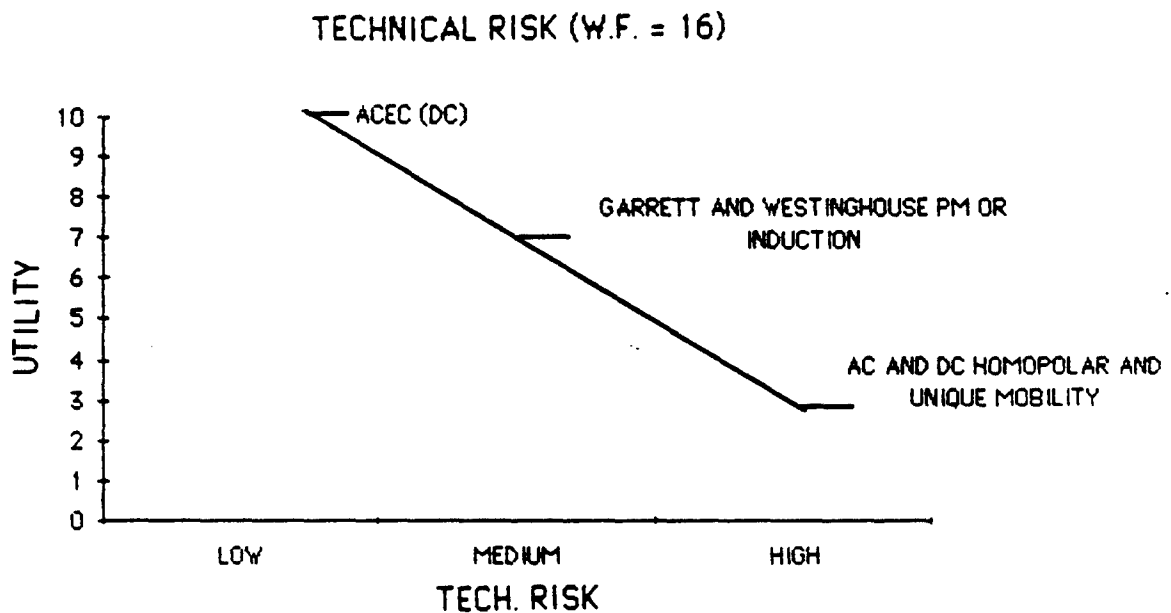


Figure 5.3-7. Utility Function for Technical Risk

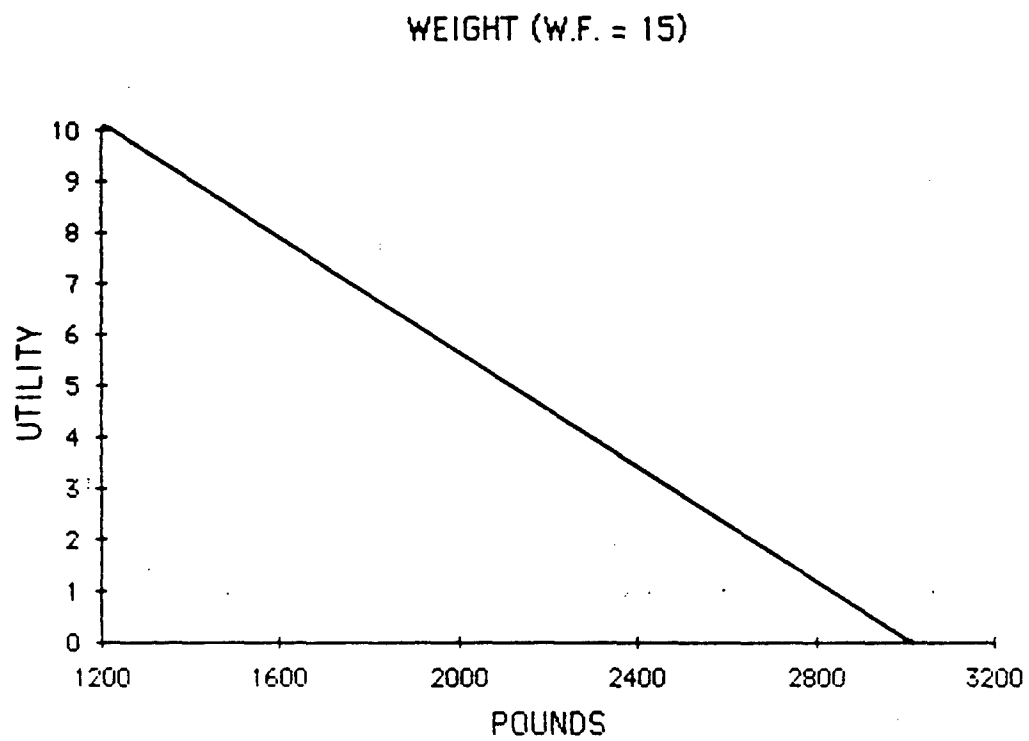


Figure 5.3-8. Utility Function for Weight, 19.5 Ton Vehicle

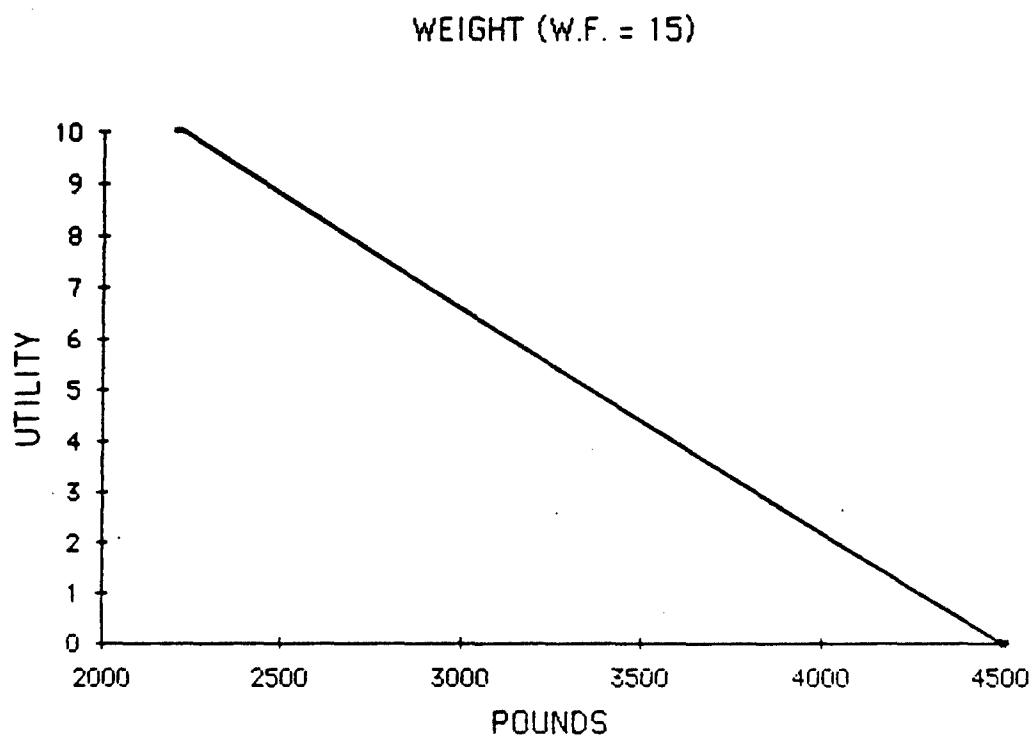


Figure 5.3-9. Utility Function for Weight, 40.0 Ton Vehicle

Reliability and Maintainability: Reliability scores were calculated utilizing a base score of ten with point deductions for appropriate concept characteristics. A two point deduction was assessed for concepts with components having special designs that are unproven at this time. Such components could possess unforeseen reliability problems which cannot be predicted in their current developmental stage. A one point deduction was assessed for brushes since they require periodic maintenance and inspection. In addition, there is a one point deduction for two speed gearboxes because of clutch wear and possible failure. Lastly, a one point deduction was assessed for concepts requiring extensive power conditioning, due to possible failure from short circuiting or overcurrent flow. Table 5.3-2 summarizes the reliability deductions for the 19.5 and 40.0 ton transmission concepts.

Safety: Safety was scored in the similar manner as reliability. A base score of 10 was utilized with point deductions for safety hazards. A two point deduction was charged for concepts with AC homopolar machinery. This is due to the liquid current collection system which contains liquid metal that is both toxic and presents a possible fire hazard. In addition, a one point deduction was assessed for oil cooling because of possible fire hazard. Table 5.3-2 summarizes these safety deductions for the 19.5 and 40.0 ton electric drive concepts.

TABLE 5.3-2. RELIABILITY AND SAFETY UTILITY DEDUCTIONS

Reliability (W.F. = 13)

- 1 BRUSHES
- 1 EXTENSIVE POWER ELECTRONICS
- 1 MULTIPLE SPEED GEARBOX
- 2 SPECIAL DESIGN

SAFETY (W.F. = 10)

- 2 AC HOMOPOLAR (LIQUID CURRENT COLLECTION)
- 1 OIL COOLING

5.3.4 Concept Scoring Results

The 38 electric drive concepts developed during the contract effort were evaluated with the screening methodology discussed in section 5.3.1. The numerical scores achieved by these 38 concepts as a result of the evaluation procedure are tabulated in table 5.3-3. The screening parameter values, utility values, and subscores for each screening factor are also given in table 5.3-3. The highest scoring electric drive concepts in the 19.5 and 40.0 ton vehicle categories are listed below:

19.5 Ton Vehicle Category

ACEC Concept I-5	826
Jarret Concept IA-3	806
Unique Mobility Concept IV-2	787
Garrett Concept I-10	779
Unique Mobility Concept I-9	779

40.0 Ton Vehicle Category

Unique Mobility Concept IV-2	782
Garrett Concept I-3	779
Unique Mobility Concept I-6	779

The best three electric drive concepts were selected from the highest scoring candidates and are (1) the ACEC Concept I-5, 19.5 ton vehicle application, (2) the Unique Mobility Concept IV-2, 19.5 and 40.0 ton vehicle applications and (3) the Garrett Concepts I-10, 19.5 ton vehicle application and I-3, 40.0 ton vehicle application. The Garrett Concepts I-10 and I-3 concepts are the same basic concept but sized for different vehicle categories. The description and analysis of the best three electric drive concepts applied to the 19.5 and 40.0 ton baseline vehicles presented in section 5.4. The reasons for not including other high scoring concepts in the best three are now addressed.

CONCEPT	MANUFACTURERS	PERFORMANCE WF = 32											TECH RISK WF = 16		WEIGHT WF = 13		RLBLTY WF = 10		SAFETY WF = 8		TOTAL SCORE (1000 POSS.)		
		TRACTION WF = 17				STEERING WF = 15							UTIL. ITY	SUB-SCORE	UTIL. ITY	SUB-SCORE	UTIL. ITY	SUB-SCORE					
		EFFICIENCY				SKID-OUT WF = 6			EFFICIENCY WF = 9														
		HP	UTIL. ITY	SUB-SCORE	RATIO	UTIL. ITY	SUB-SCORE	REGEN. EFF.	UTIL. ITY	SUB-SCORE	FT ²	UTIL. ITY							SUB-SCORE	LBS.		UTIL. ITY	SUB-SCORE
	19.5 TON																						
I-1	GARRETT PM GENERATOR AND MOTORS	324	6.8	116	.917	8.4	50	.68	6.8	61	15.2	7.5	158	5	80	2062	5.2	60	8	80	9	72	685
I-2	WESTINGHOUSE IND MOTOR/WR GEN.	316	5.6	95	.696	8	0	.65	5.8	52	16.93	4.7	99	5	80	1917	6.0	78	8	80	9	72	556
I-3	WESTINGHOUSE PM MOTOR/WR GEN.	312	5.1	87	.695	0	0	.63	5.4	49	18.24	5.2	109	5	80	1642	7.5	98	8	80	9	72	575
I-4	ACEC DC MOTORS/RECT. AC GEN.	354	9.4	160	.987	9.9	59	.79	8.8	79	21.8	2.5	53	8	128	2891	.6	8	8	80	10	80	647
I-5	ACEC DC MOTORS/ GARRETT PM GEN.	346	9.0	153	.995	9.9	59	.79	8.8	78	11.93	10	210	7	112	2160	4.7	61	8	80	9	72	826
I-6	GARRETT PM GEN. AND MOTOR COMBINATION	333	7.8	133	.950	9.0	54	.70	7.2	65	15.06	7.6	160	7	112	2464	3.8	39	9	90	9	72	726
I-7	WESTINGHOUSE DC HOMO GEN. AND MOTORS	354	9.5	162	.996	9.9	59	.78	8.7	78	14.46	8.1	170	3.5	56	3311	0	0	7	70	9	72	667
I-8	U OF M AC HOMO GEN. / WESTINGHOUSE IND. MOTORS	342	8.7	148	.702	8	0	.76	8.3	75	18.2	5.2	109	1.5	24	2313	3.8	49	6	60	7	56	521
I-9	UNIQUE MOBILITY SELF-SYNC MTRS/ GARRETT PM GEN.	350	9.3	158	.696	0	0	.82	9.2	83	11.79	10	210	3.5	56	1188	10	130	7	70	9	72	779
I-10	GARRETT PM GEN. AND MOTORS	333	7.8	133	.947	9.0	54	.78	7.2	65	12.1	9.9	208	5	80	1800	6.7	87	8	80	9	72	770
IIA-1	GARRETT PM GEN. AND MOTORS (MOUNTED INSIDE SPROCKETS)	324	6.8	116	.917	8.4	50	.68	6.8	61	12.76	9.4	197	5	80	2540	2.6	34	8	80	9	72	690
IIA-2	JARRET VR MOTORS/ GARRETT PM GEN. (DIRECT DRIVE)	356	9.6	163	.99	9.9	59	.83	9.3	84	38.4	0	0	5	80	4375	0	0	9	90	9	72	548
IIA-3	JARRET VR MOTORS/ GARRETT PM GEN. (10:1 RATIO)	346	9.0	153	.99	9.9	59	.80	8.9	80	13.8	8.6	181	5	80	1735	7.0	91	9	90	9	72	806
II-1	GARRETT PM GENERATOR AND MOTOR	324	6.8	116	1.0	10.0	60	.92	10	98	14.59	6.0	126	7	112	1900	6.1	79	8	80	9	72	735
II-2	WESTINGHOUSE GENERATOR PM CLUSTER AND STEER MOTORS	312	5.0	85	1.0	10.0	60	.92	10	90	17.38	3.9	82	7	112	1872	6.3	82	8	80	9	72	683
II-3	GARRETT PM GENERATOR/ ACEC DC MOTOR	346	9.0	153	1.0	10.0	60	.92	10	90	14.03	6.4	134	7	112	2151	4.7	61	8	80	9	72	762
II-4	WESTINGHOUSE DC HOMO GEN. AND MOTOR	363	10.0	170	1.0	10.0	60	.92	10	90	15.44	5.4	113	3.5	56	3161	0	0	7	70	9	72	631
II-5	U OF M AC HOMO GEN. / WESTINGHOUSE IND. MTR CLSTR	342	8.7	148	1.0	10.0	60	.92	10	90	16.5	4.5	95	1.5	24	2260	4.1	53	6	78	7	56	586
II-6	UNIQUE MOBILITY/SELF SYNC MOTORS/GARRETT PM GEN	350	9.3	158	1.0	10.0	60	.92	10	90	13.5	8.8	143	3.5	56	1490	8.3	108	7	70	9	72	757

TABLE 5.3-3. CANDIDATE CONCEPT SCORING SUMMARY

CONCEPT	MANUFACTURERS	PERFORMANCE WF = 32												TOTAL SCORE (1000 POSS.)										
		TRACTION WF = 17				EFFICIENCY WF = 15																		
		STEERING WF = 9				SKID-OUT WF = 6				REGEN. EFF.														
		UTIL- ITY	SUB- SCORE	RATIO	UTIL- ITY	SUB- SCORE	UTIL- ITY	REGEN. EFF.	UTIL- ITY	SUB- SCORE	UTIL- ITY	SUB- SCORE												
III-1	GARRETT PM GENERATOR, PROPULSION AND STEER MTRS	324	6.8	116	1.0	10.0	60	89	89	9.9	89	16.75	5.3	111	5	80	2080	5.1	66	8	80	9	72	674
III-2	ACEC DC PROP AND STEER MTRS/ GARRETT PM GENERATOR	345	9.0	153	1.0	10.0	60	89	89	9.9	89	13.20	7.5	157	7	112	2031	5.4	70	8	80	9	72	773
III-3	UNIQ MBLY PROP & STEER MTRS/ GARRETT PM GENERATOR	350	9.6	163	1.0	10.0	60	89	89	9.9	89	14.69	6.9	146	3.5	56	1478	8.4	109	7	70	9	72	765
IV-1	GARRETT PM GENERATOR AND MOTORS	342	8.8	150	1.0	10.0	60	79	79	8.8	79	17.06	4.1	96	5	80	2145	4.8	62	8	80	9	72	669
IV-2	UNIQUE MOBILITY PM MOTOR/ GARRETT PM GEN.	367	10.0	170	1.0	10.0	60	86	86	9.6	84	12.53	7.6	160	3.5	56	1438	8.7	113	7	70	9	72	785
IV-3	ACEC DC MOTORS/ GARRETT PM GEN.	359	9.7	165	1.0	10.0	60	85	85	9.6	84	13.57	6.5	136	7	112	2084	5.1	66	8	80	9	72	777
I-1	GARRETT PM GENERATOR AND MOTORS	658	5.7	97	8.68	7.6	46	68	68	6.8	60	21.23	4.7	141	5	80	3374	4.9	64	8	80	9	72	640
I-2	ACEC DC MOTORS/ GARRETT PM GENERATOR	710	9.3	158	9.55	9.2	55	79	79	8.8	79	21.16	6.8	143	7	112	4090	1.8	23	8	80	9	72	722
I-3	GARRETT PM GEN. AND MOTORS	675	7.3	124	8.91	8.1	49	71	71	7.3	64	16.7	10	210	5	80	2780	7.5	98	8	80	9	72	777
I-4	WESTINGHOUSE DC HOMO GEN. AND MOTORS	726	10.0	170	9.60	9.4	56	83	83	9.3	82	19.53	8.1	170	3.5	56	4916	0	0	7	70	9	72	676
I-5	U OF M HOMO GENERATOR/ WESTINGHOUSE IND. MTR CLSTR	701	9.0	153	6.49	0	0	76	76	8.3	73	19.89	7.8	164	1.5	24	3220	5.6	73	6	60	7	56	603
I-6	UNIQUE MBLY SELF-SYNC MTRS/ GARRETT PM GENERATOR	710	9.3	158	8.96	0	0	82	82	9.2	81	17.03	10	210	3.5	56	1937	10.0	130	7	70	9	72	777
II-1	WESTINGHOUSE DC HOMOPOLAR GEN. AND MOTOR	726	10.0	170	1.0	10.0	60	92	92	10	96	20.42	5.5	116	3.5	56	4466	0	0	7	70	9	72	634
II-2	U OF M AC HOMO GENERATOR/ WESTINGHOUSE IND. MTR CLSTR	701	9.0	153	1.0	10.0	60	92	92	10	90	22.79	3.5	74	1.5	24	3370	4.9	64	6	60	7	56	581
II-3	WESTINGHOUSE PM GENERATOR, AND CLUSTER MOTOR	658	5.7	97	1.0	10.0	60	92	92	10	90	24.85	2.0	42	5	80	2883	7.0	91	8	80	9	72	612
II-4	UNIQUE MBLY SELF-SYNC MTRS/ GARRETT PM GENERATOR	709	9.3	158	1.0	10.0	60	92	92	10	90	19.46	8.1	128	3.5	56	2330	9.4	122	7	70	9	72	758
III-1	GARRETT PM GEN. AND MOTORS	659	5.7	97	1.0	10.0	60	89	89	9.9	89	22.30	4.9	103	5	80	2964	6.7	87	8	80	9	72	666
IV-1	GARRETT PM GEN. AND MOTORS	708	9.3	158	1.0	10.0	60	79	79	8.8	77	19.63	6.0	126	5	80	2962	6.7	87	8	87	9	72	740
IV-2	UNIQUE MBLY SELF-SYNC MTRS/ GARRETT PM GENERATOR	726	10.0	170	1.0	10.0	60	86	86	9.6	85	18.71	6.7	141	3.5	56	2237	9.8	127	7	70	9	72	781

TABLE 5.3-3. CANDIDATE CONCEPT SCORING SUMMARY (Continued)

The Jarret Concept IA-3, which uses the variable reluctance motor, is the highest scoring concept; however it was not included in the best three because the concept data was received very late in the study and time did not allow a thorough investigation of this concept. It is recommended that this concept be thoroughly investigated at the earliest opportunity due its high potential and favorable characteristics. The Jarret concept embodies important features which includes: the use of a single speed gearbox, high motor torque production relative to motor size, minimum power electronics relative to motor size, minimum power electronics relative to other AC systems, and potential low unit production cost.

The scores of the Unique Mobility Concepts, I-9 and I-6, and Garrett Concepts I-10 and I-3, are essentially the same. The Garrett concepts were selected over the Unique Mobility concepts due to the lower technical risk and greater intermittent duty capability of the Garrett traction motor, notwithstanding that these factors have been accounted for in the evaluation procedure. The Unique Mobility concepts, I-9 and I-6 are very good alternative concepts that should be considered in future studies.

5.4 DESCRIPTION OF BEST THREE CONCEPTS

The best three electric drive concepts were determined in section 5.3 and are:

- o ACEC Configuration I, Concept 5 (19.5 ton)
- o Garrett Configuration I, Concept 10 (19.5 ton) and Concept 3 (40.0 ton)
- o Unique Mobility Configuration IV, Concept 2 (19.5 ton) and Concept 2 (40.0 ton)

The ACEC concept is applied to the 19.5 ton vehicle only while the Garrett and Unique Mobility concepts are applied to be vehicle weight categories. This section describes the three best electric drive concepts in terms of their physical and performance characteristics when applied to the 19.5 ton and 40.0 baseline vehicles.

5.4.1 ACEC Configuration I, Concept 5, 19.5 Ton Vehicle Application

ACEC concept I-5 has a DC traction motor, two speed gearbox, and a final drive at each drive sprocket. Traction motor power is supplied by a permanent magnet AC generator whose output is rectified to DC. An ECU supervises the electric drive system and the power plant in response to operator commands to provide the desired propulsion, steer, and brake performance within the limits of the system. Figure 5.4-1 presents a schematic of the ACEC concept for the 19.5 ton vehicle. Table 5.4-1 presents a summary of the physical characteristics of the ACEC concepts for the 19.5 ton vehicle. A three view layout drawing of the ACEC electric drive concept installed in the 19.5 ton baseline vehicle with the cummins VTA-903T engine and other power pack subsystems is shown in figure 5.4-2.

The ACEC concept has the lowest technical risk of the three best concepts. The DC traction motor technology required for this concept is a well established technology that is employed and demonstrated in current ACEC, limited production units of similar power rating. The PM generator is a developmental Garrett design based on technology that has been demonstrated by prototype hardware. The other element of this transmission concept (rectifier, ECU, and two speed gearbox) require custom designs with little or no technical risk.

No unusual materials or processes are identified for this concept. The samarium cobalt permanent magnets and the nickel alloy (inconel) used in the PM generator have been used in the manufacture of electric machinery for the last 10 to 12 years. However, cobalt is on the strategic materials list and the permanent magnets require special handling on the production line to prevent fracture and contamination.

The unit production cost of the ACEC concept I-5 for the 19.5 baseline vehicle based on total production of 400 units is projected to be 100 K dollars. This cost does not include final drive, cooling system, and integration hardware costs. The major cost item is the DC traction motor which has high labor content in the manufacture of the wound rotor, the wound stator, and the mechanical commutator.

ACEC 19.5 TON SCHEMATIC

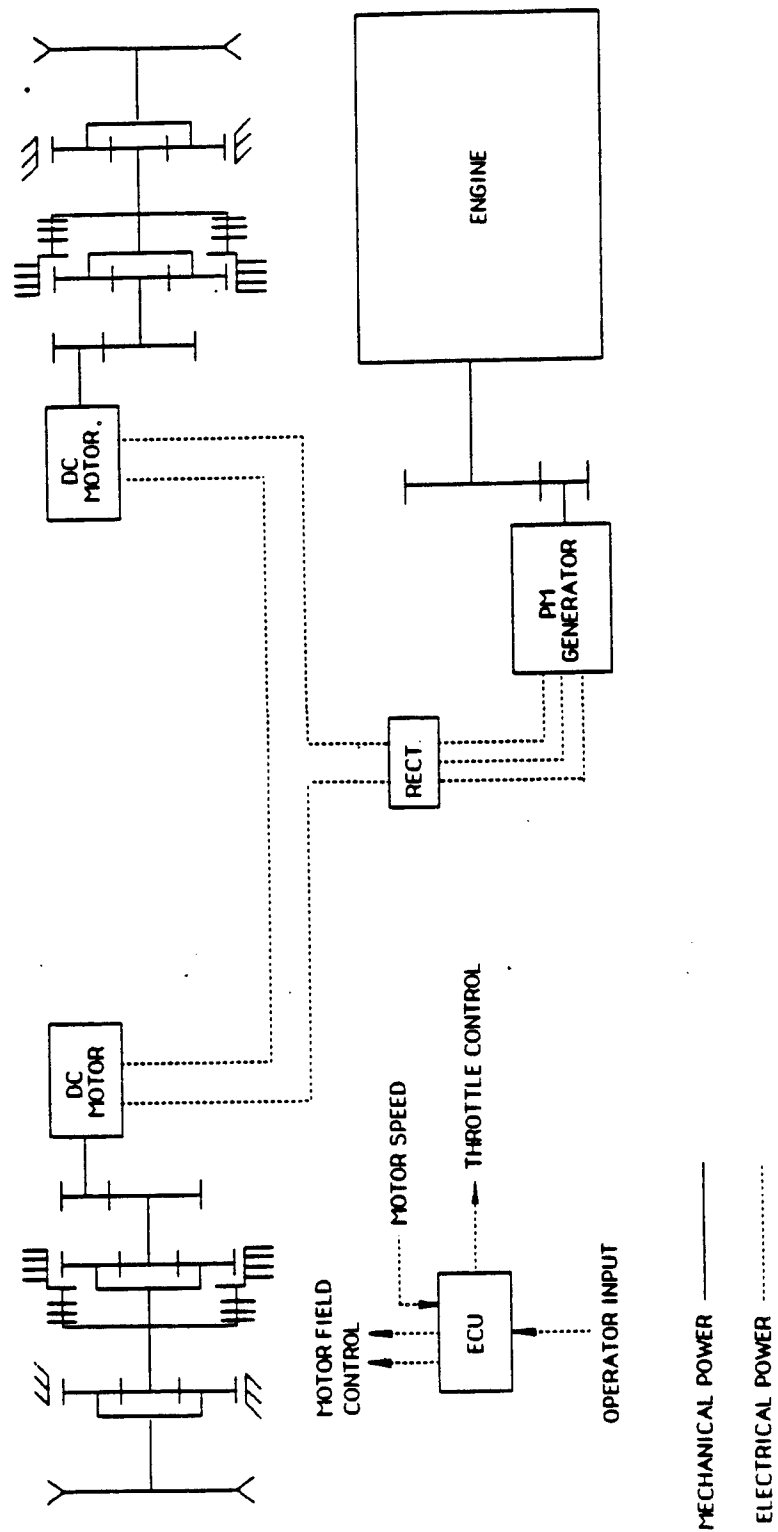
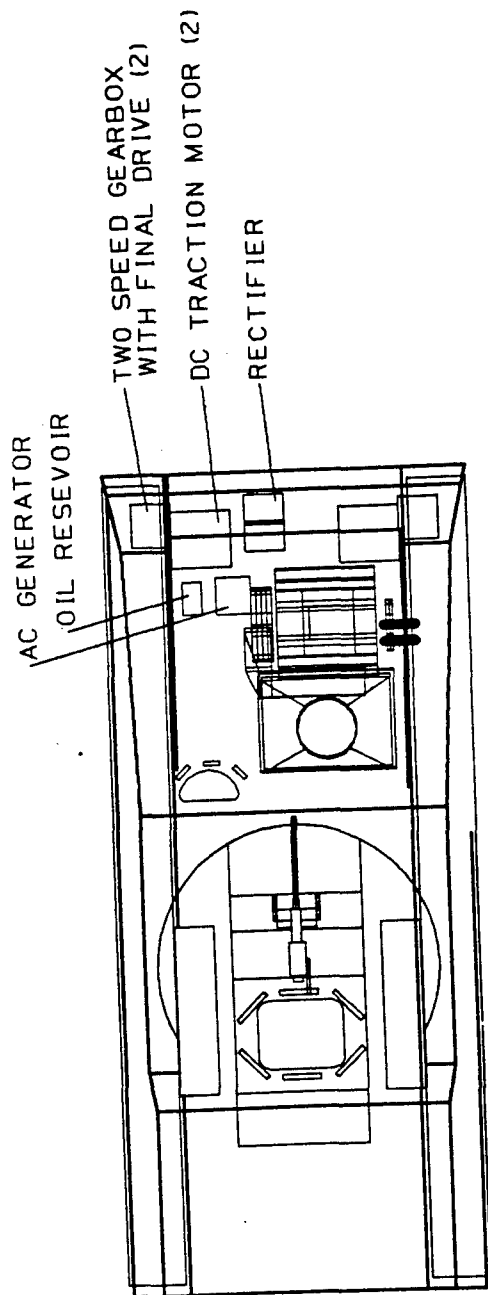


Figure 5.4-1. ACEC Concept I-5, 19.5 Ton, Schematic

TABLE 5.4-1. ACEC CONCEPT I-5 TRANSMISSION CHARACTERISTICS

VEHICLE GW 19.5 TON
CONF. I
CONCEPT 5

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Weight Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 9.3		.53	110	110	417	93.5	18000 rpm
2	DC Traction Motor	16.9 dia x 18.1	2.35	4.70	700	1400	192	95-92	1880-5660 rpm
1	Rectifier	12 x 12 x 12		1.00		100		98	
1	ECU	8 x 8 x 8		.30		20			Includes Motor Excitation System
2	2 Speed Gearbox	14 dia x 8	.75	1.50	40	80		98-96	6.7:7 Lo 2.2:1 Hi
1	Transfer Case	14 dia x 6		.53		125		98	
1	Cooling System Air & Oil			2.00		200			Max Heat Rejection 3440 Btu/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cables					15			
TOTAL:				10.96		2160		81 avg. (80-84)	



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19.5 TON ACEC
CONCEPT I-5
DWG. NO. AD-8432-0023

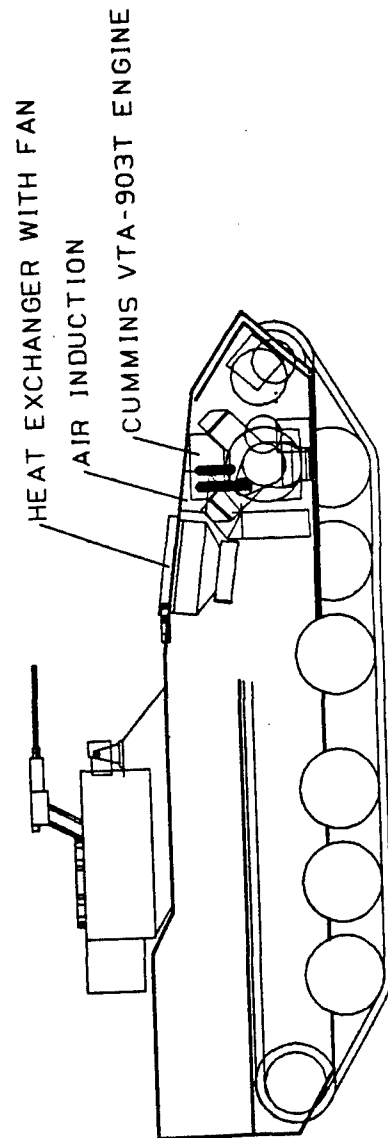
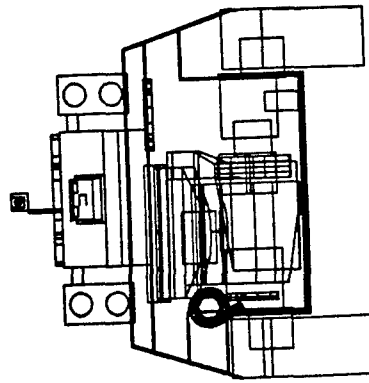


Figure 5.4-2. ACEC Concept I-5, 19.5 Ton Vehicle Installation

5.4.1.1 Generator

The generator is a Garrett self-excited, brushless, oil cooled, PM machine rated at 417 HP. The generator uses rare earth cobalt permanent magnets to supply the field flux thus eliminating the need for collection brushes. The generator's operating speed is 18,000 rpm, which dictates the use of a 6.9:1 ratio transfer case to raise the engine speed to the operating speed of the generator.

Generator Characteristics

Rating	370 KVA
Speed	18000 RPM
Efficiency	93.5%
Voltage	747 Vrms Line to Line
Cooling	Oil Cooled

5.4.1.2 Rectifier

The generated three phase AC power must be rectified to DC for the traction motors. This is done by a six thyristor rectifier bridge shown in figure 5.4-3. The use of thyristors as opposed to diodes allows bi-directional power flow and voltage control.

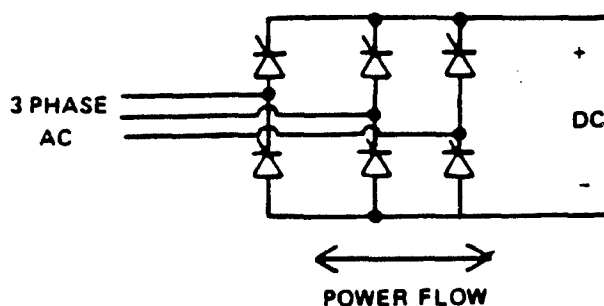


Figure 5.4-3. Rectifier Bridge Schematic

Rectifier Characteristics

Rating	370 KVA
Efficiency	98%
Voltage	747 Vdc
Current	367 DC AMPS
Cooling	Oil Cooled

5.4.1.3 Traction Motors

The two ACEC traction motors are separately excited, air cooled, DC machines, rated at 192 HP. The motor's rotor and stator are conventionally wound. The motor's field excitation is controlled by the ECU. The motors are capable of delivering three times the rated power for up to 20 seconds. The DC motor is capable of acting as a generator when its field excitation voltage is reversed. This mode is employed during steering and braking. The power generated is fed back into the system and added to the permanent magnet generator's power. The motors are estimated to weigh 700 lbs, with an outside diameter of 16.9 inches and an overall length of 18.1 inches. The torque and efficiency of the ACEC 192 horsepower motor are shown in figure 5.4-4 as a function of motor speed.

Rectifier Characteristics

Rating	192 HP
Efficiency	93 percent at base speed
Base Speed	1887 RPM
Max Rated Speed	5660 RPM
Voltage	420 Vdc
Current	367 DC AMPS
Cooling	Air Cooled

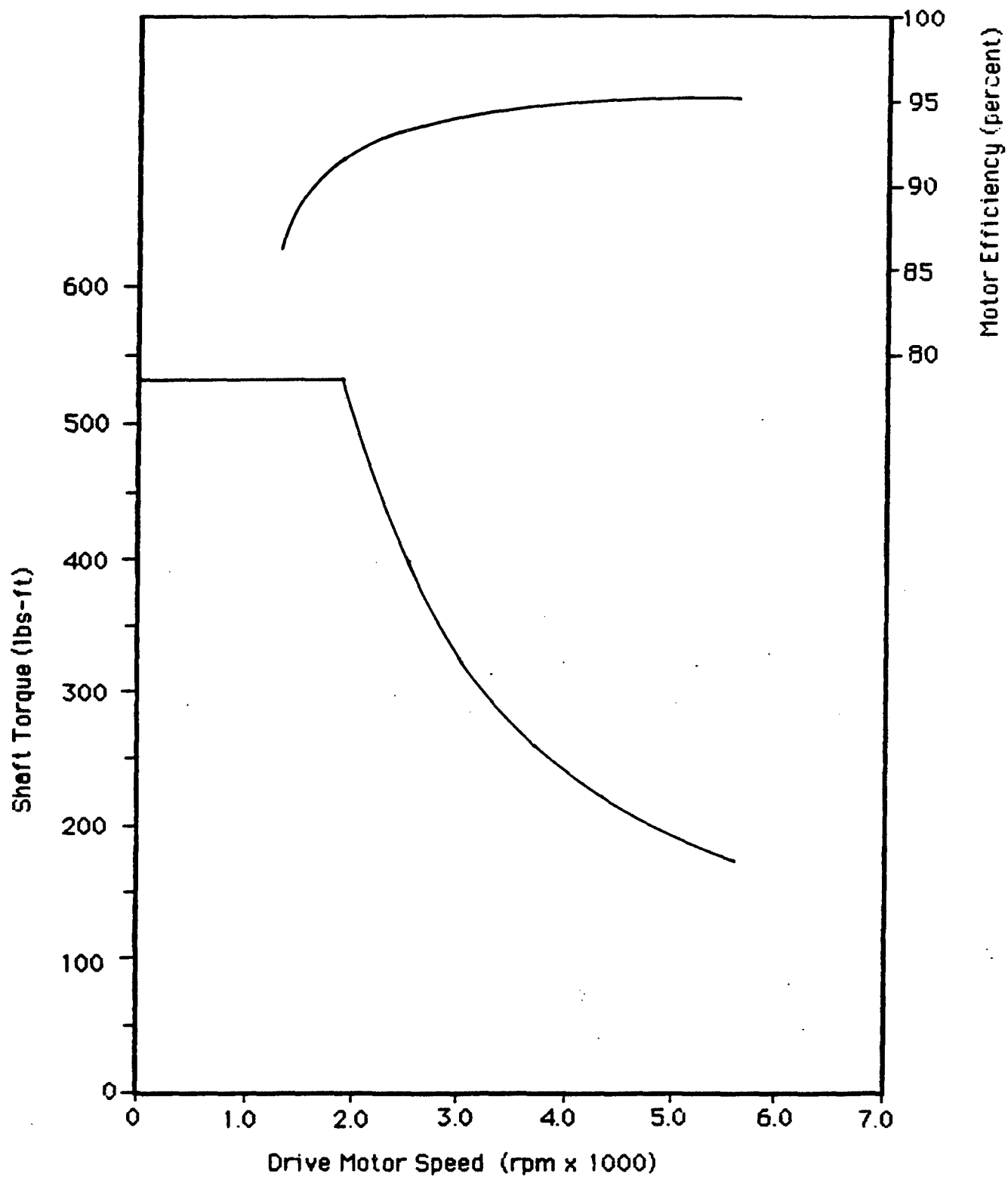


Figure 5.4-4. Torque and Efficiency Versus Speed
for 192 Horsepower ACEC DC Motor

5.4.1.4 Two Speed Gearbox

The DC traction motor delivers rated power over a 3 to 1 speed range (from base speed to maximum rated speed) which is not sufficient to provide the required tractive effort over the vehicle speed range of 5 to 45 miles per hour. A two speed, oil cooled gearbox with a 3:1 ratio step in combination with the DC traction motor is utilized to cover the 9 to 1 vehicle constant power speed range. The first stage of the two speed gearbox consists of a two gear set which provides a 2.242:1 reduction and also results in an offset configuration which is beneficial to front drive installations (see figure 5.4-1). The second stage is a planetary gear set with two clutches which provides a 3:1 reduction in low gear (clutch 1 engaged, clutch 2 disengaged) and results in a total reduction of 6.73:1 when combined with the first stage gear set. In high gear (clutch 1 disengaged, clutch 2 engaged), the second stage is in coupling mode (sun, ring, and carrier have the same rotation rate) providing a 1:1 ratio which results in a total reduction of 2.24:1 when combined with the first stage gear set.

Although the 3:1 ratio step of the two-speed gearbox is considerably wider than the current norm, no insurmountable problems are anticipated. The use of constant mesh gearing and clutch modulation during shifting is currently applied to the X-1100 transmission of the M1. The ability to rapidly change motor speed will minimize transient gearbox loads and provide smooth shifting while the 3:1 rated-power speed ratio of the motor will enable the delivery of rated power on a continuous basis (except during actual shift implementation). The shifting process is expected to have a duration of approximately three quarters of a second.

Shift controlling will be accomplished by the automotive subsystem micro-processor as a function of motor speed, vehicle speed, and vehicle turn rate. Other parameters which may also provide input could be power level, brake application status or throttle position. The sequence of events comprising shift implementation would be as follows (several of these actions would be performed simultaneously):

- o Remove power from motors.
- o Disengage clutch #1
- o Command new motor speed.
- o Engage clutch #2 within synchronous band of motor speed.
- o Confirm shift completion.
- o Resume command power operation.

A bilateral shift control scheme could accommodate unilateral shifts via repeat commands or restricted operations to prevent a damaging drive motor overspeed condition. A unilateral shift control scheme would independently control the gearbox shift status on each side, although the same protective algorithms would apply.

In the event of a mechanical failure of either shift mechanism, both gearboxes could be manually locked into either speed range to ensure continued, although reduced, performance operation. The choice of speed range would be predicated on the tactical conditions at the time of the failure.

Shift controlling when the vehicle is operating at the shift point would be stabilized via the use of hysteresis band to prevent shift "dithering." This band would be of variable width as a function of vehicle turning rate to accommodate the differential speeds within the rated-power speed range of the drive motors.

The inability of the electric drive motors of this concept to provide a rated-power speed band of sufficient width to satisfy vehicle mobility requirements mandates the inclusion of a two-speed gearbox. Although the addition of these gearboxes adds to the overall system complexity, they do not present any performance or control problems that cannot be satisfactorily addressed using state-of-the-art micro-processor control technology.

5.4.1.5 Final Drive

The final drive is a concentric, self contained, heavy duty planetary gear set with a 4:1 reduction ratio. The output of the two speed gearbox is input to the final drive at the planetary sun gear. The planetary ring gear is bolted

to the final drive housing and is stationary. The planet carrier is coupled to the drive sprocket. The two speed gear box and final drive provide a total reduction of 26.92:1 in low and 8.97:1 in high. The pitch diameter of the drive sprockets is 24 inches.

5.4.2 Garrett Configuration I, Concept 10, 19.5 Ton Vehicle Application

The Garrett concept I-10 uses a permanent magnet AC synchronous traction motor, two speed gearbox, and final drive at each drive sprocket. Traction motor power is supplied by a permanent magnet AC generator whose output is conditioned by a rectifier and individual motor inverter units. An ECU supervises the electric drive system and the power plant in response to operator commands to provide the desired propulsion, steer, and braking performance within the limits of the system. A schematic of the Garrett concept I-10 for the 19.5 ton vehicle category is presented in figure 5.4-5. Table 5.4-2 presents a summary of the transmission characteristics for the 19.5 ton Garrett concept. A three view layout drawing on the Garrett concept installed in the 19.5 ton baseline vehicle with the cummins VTA-903T engine and other power pack subsystems is shown in figure 5.4-6.

5.4.2.1 Generator

The AC generator is a Garrett, self-excited, brushless, oil cooled, permanent magnet machine rated at 444 horsepower. The generator uses rare earth cobalt permanent magnets to supply the field flux. The generators rated speed is 18,000 RPM, which dictates the use of 6.9:1 ratio speed increaser transfer case to raise the engine speed to the rated generator speed.

The Garrett concept is considered to have medium technical risk. The PM traction motor, the PM generator, and the power conditioner units are developmental designs which have been demonstrated in scaled-down prototype hardware. The GDLS electric vehicle test bed uses electric drive components which are based on this technology. The two speed gearbox is a customer design which has low technical risk.

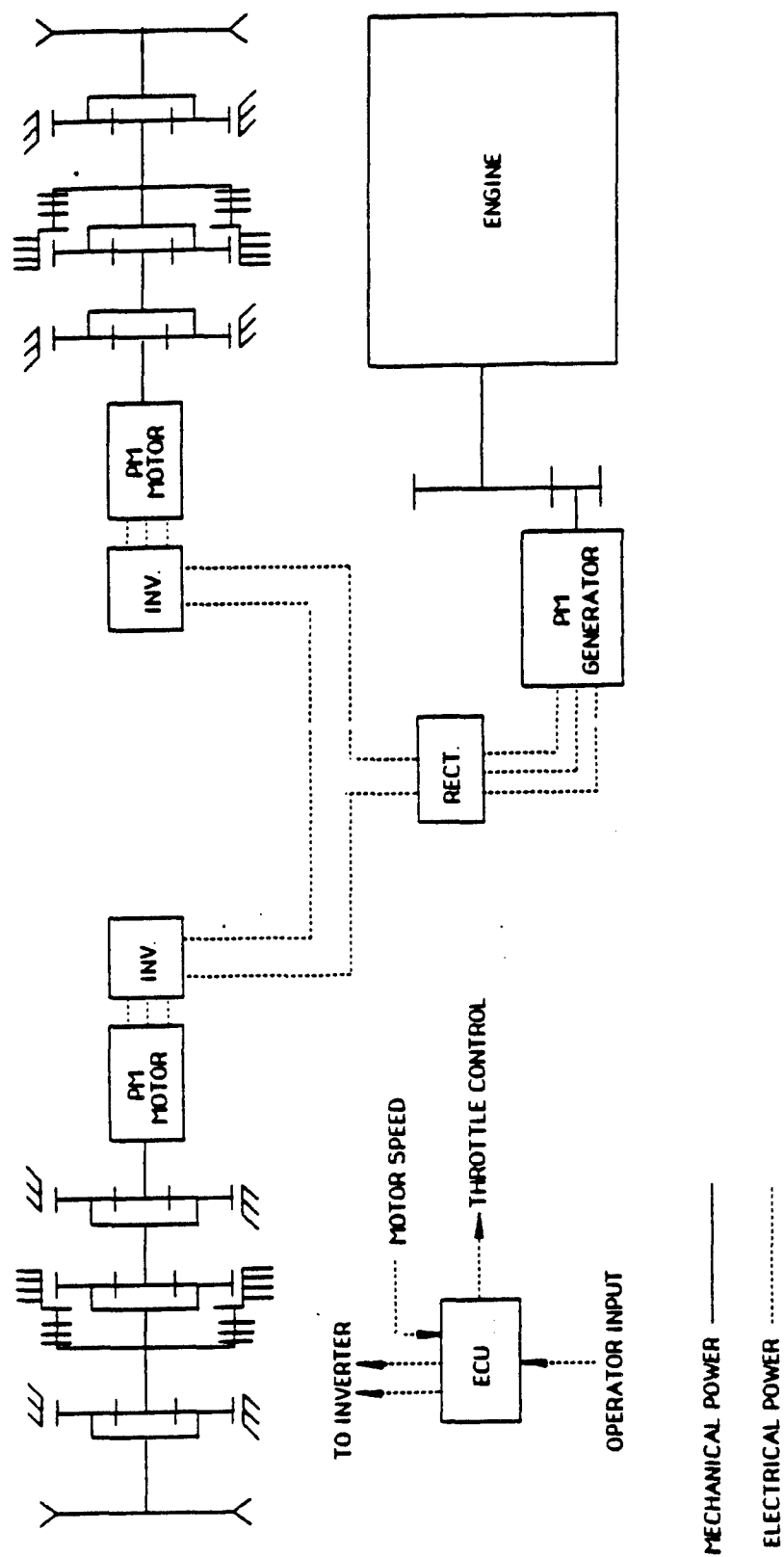
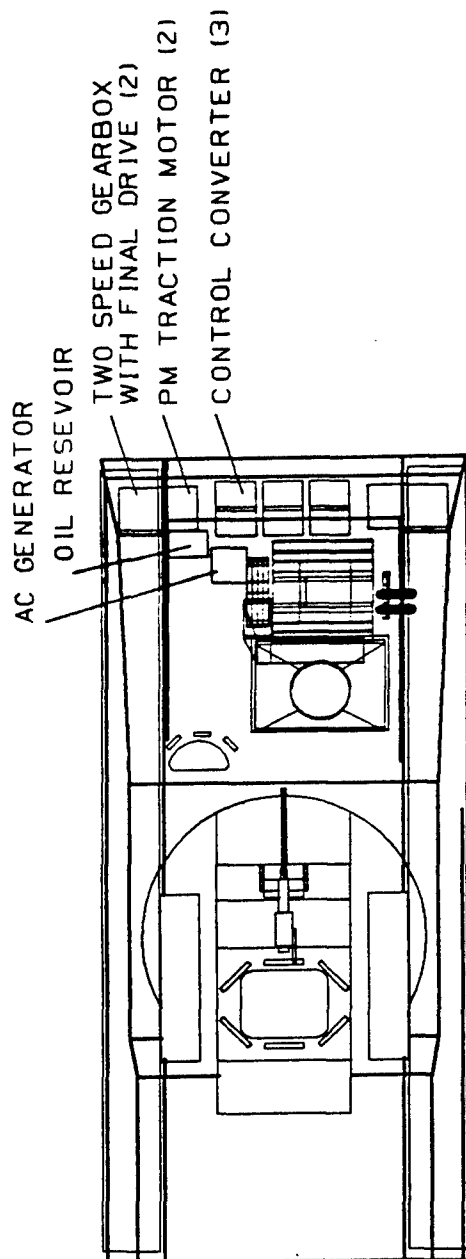


Figure 5.4-5. Garrett Concept I-10, 19.5 Ton Schematic

TABLE 5.4-2. GARRETT CONCEPT I-10 TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON
CONF. I
CONCEPT 10

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.5		.60		125	444	93.5	18000 rpm
3	PCU	12 x 10 x 12	.83	2.50	83	250	218	96	
2	Traction Motor	13.5 dia x 12.4	1.02	2.04	330	660	192	93-90	4600, 18000 rpm
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 6	.75	.53		125		98	6.9:1 Ratio
2	2 Speed Gearbox	14 dia x 13.5	1.25	2.50	55	110		98-96	16.4:1 Lo 5.5:1 Hi
1	Oil Cooling System			2.80		360			Max Heat Rejection 4000 BUT/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cables					20			
TOTAL:				12.20		1800		78 avg. (76-80)	



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19.5 TON GARRETT
CONCEPT I-10

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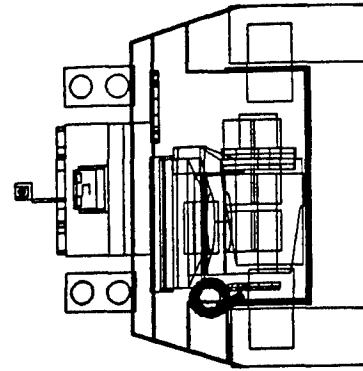
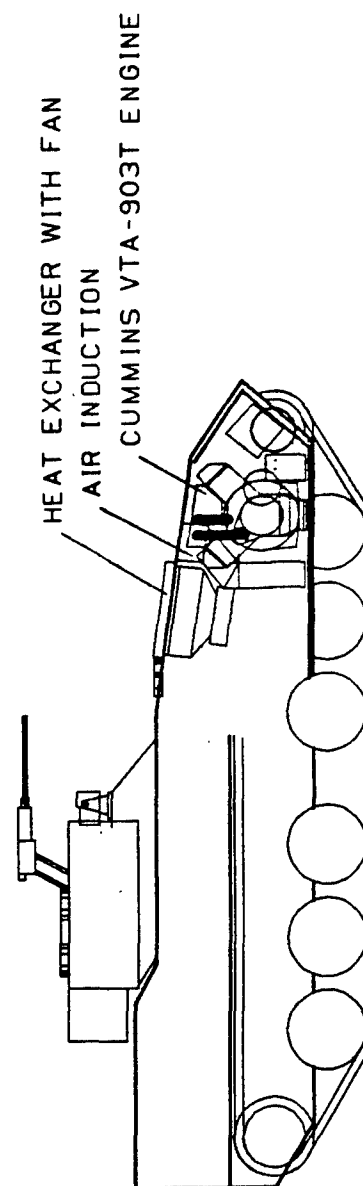


Figure 5.4-6. Garrett Concept I-10, 19.5 Ton Vehicle Installation

No unusual materials or processes are identified for this concept. The traction motors and generator use samarium cobalt permanent magnets and nickel super alloys in their manufacture. Cobalt is a strategic material, and the cobalt magnetics require special handling during the production process.

The unit production cost of the Garrett Concept I-10 based on a total production of 400 units is projected to be 165 K dollars. This includes the unit costs of one generator, two traction motors, two power conditioning units, and two 2-speed gearboxes.

Generator Characteristics

Rating	370 KVA
Speed	18000 RPM
Efficiency	93.5%
Voltage	747 Vrms Line to Line
Cooling	Oil Cooling

5.4.2.2 Rectifier

The rectifier is basically a phase delay rectifier. It performs two primary functions: rectification of the input AC source (generator AC output) and regulation of current to inverter. The converter operation is bilateral, enabling it to receive and channel the reverse or regenerative power from the load (motor) to the input AC source (alternator). This is an important consideration for the dynamic braking and skid-steer situations. The rectifier unit contains voltage and current sensors which provide feedback signals to the ECU. Figure 5.4-3 shows the rectifier bridge.

Rectifier Characteristics

Rating	370 KVA
Efficiency	98%
Voltage	747 Vdc
Current	367 DC AMPS
Cooling	Oil Cooled

5.4.2.3 Inverter

The inverter performs the commutation function for the AC drive motors. The inverter is a line commutated type, whereby the thyristors are turned off by the back EMF of the motors. At speed conditions below 10% rated, when the back EMF is too low to affect thyristor turn-over, a low frequency modulation (blanking) is imposed to provide forced commutation. The inverter unit operation is bilateral similar to the rectifier so that it can act as a rectifier during steering or braking; the phase delay rectifier then acts as an inverter thus coupling power back into the system. The inverter schematic is shown in figure 5.4-7.

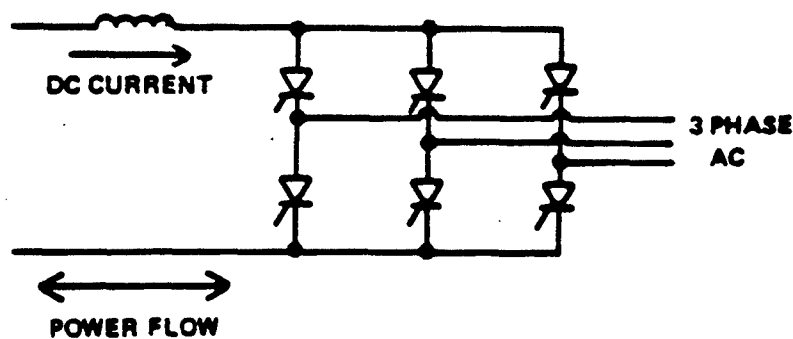


Figure 5.4-7 SCR Inverter Schematic

Inverter Characteristics

Efficiency	96%
Voltage	310 Vac
Current	367 AMPS
Cooling	Oil Cooled

5.4.2.4 Traction Motor

The permanent magnet synchronous motors are constructed with an oil-cooled conventional 3-phase stator winding. The stator case is laminated silicon steel with relatively wide teeth and thick back iron to provide low flux density and low core losses. The stator is wound with ML coated wire and impregnated with ML varnish.

The rotor consists of radially oriented samarium cobalt magnets and a ferromagnetic core with an inconel sleeve to provide structural support. The rotor is an eight pole design. The traction motor can deliver three times the rated power for up to 30 seconds duration. The torque and efficiency of the Garrett 192 horsepower motor versus motor speed are given in figure 5.4-8.

Motor Characteristics

Rating	192 HP
Efficiency	93 percent at base speed
Base Speed	4,600 RPM
Max. Rated Speed	18,500 RPM
Voltage	310 Vrms Line to Line
Cooling	Oil Cooled

5.4.2.4 Two Speed Gearbox

The AC traction motor delivers rated power over a 4 to 1 speed range (from base speed to maximum rated speed) which is not sufficient to provide the required tractive effort over the vehicle speed range of 5 to 45 miles per hour. A two speed oil cooled gearbox with a 3:1 ratio step in combination with the AC traction motor is utilized to cover the 9 to 1 vehicle constant power speed range. The first stage of the two speed gearbox consists of a planetary gear set which provides a 5.466:1 reduction (see figure 5.4-5). The second stage is a planetary gear set with two clutches which provides a 3:1 reduction in low gear (clutch 1 engaged, clutch 2 disengaged) and results in a

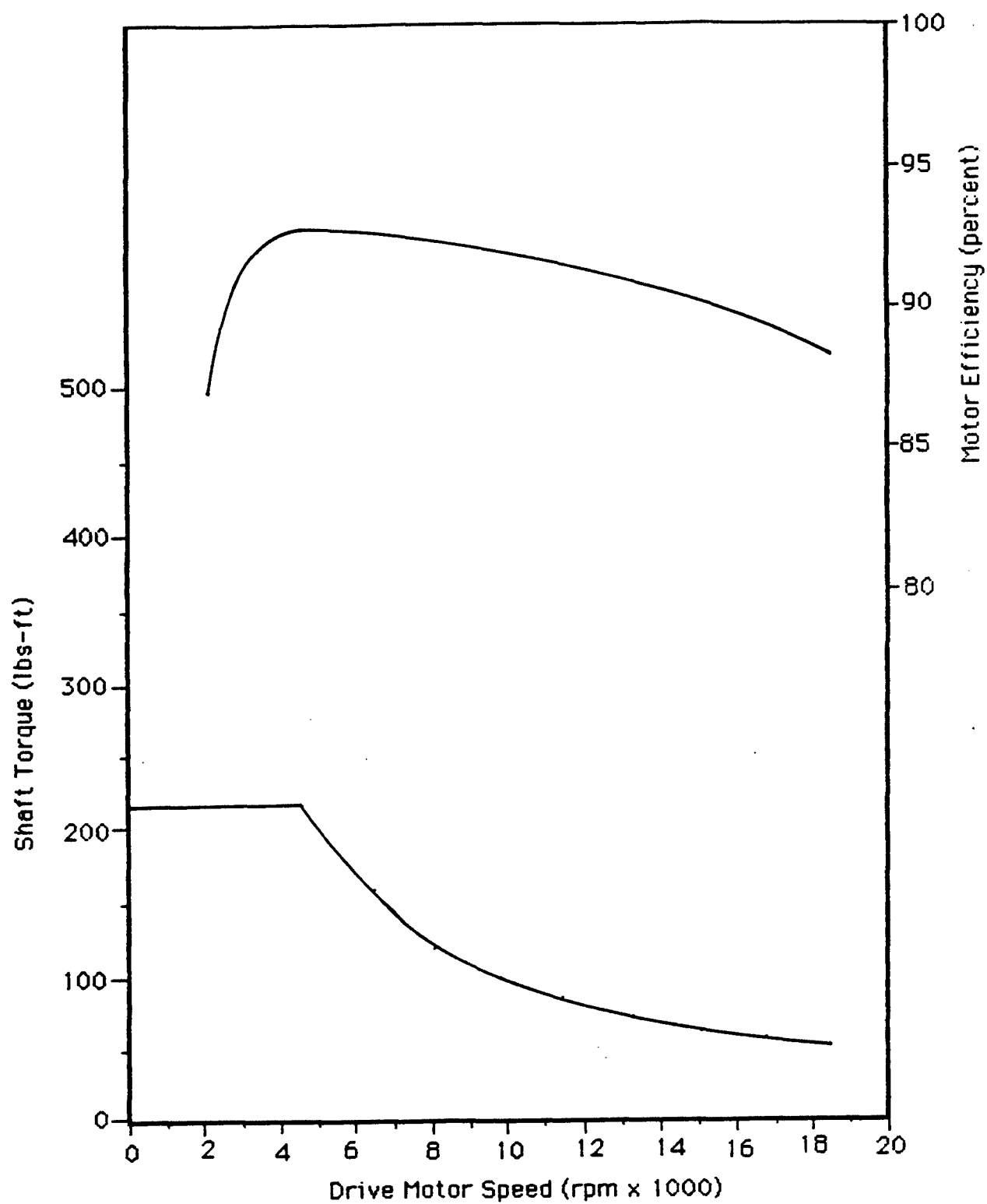


Figure 5.4-8 Torque and Efficiency Versus Speed
for 192 Horsepower Garrett PM Motor

total reduction of 16.4:1 when combined with the first stage gearset. In high gear (clutch 1 disengaged, clutch 2 engaged) the second stage is in coupling mode (sun, ring, and carrier has the same rotation rate) providing a 1:1 ratio which results in a total reduction of 5.466:1 when combined with the first stage planetary set.

Although the 3:1 ratio step of the two-speed gearbox is considerably wider than the current norm, no insurmountable problems are anticipated. The use of constant mesh gearing and clutch modulation during shifting is currently applied to the X-1100 transmission of the M1. The ability to rapidly change motor speed will minimize transient gearbox loads and provide smooth shifting while the 3:1 rated-power speed ratio of the motor will enable the delivery of rated power on a continuous basis (except during actual shift implementation). The shifting process is expected to have a duration of approximately three quarters of a second.

Shift controlling will be accomplished by the automotive subsystem micro-processor as a function of motor speed, vehicle speed, and vehicle turn rate. Other possible parameters which may also provide input could be power level, brake application status or throttle position. The sequence of events comprising shift implementation would be as follows (several of these actions would be performed simultaneously):

- o Remove power from motors.
- o Disengage clutch #1.
- o Command new motor speed.
- o Engage clutch #2 within synchronous band of motor speed.
- o Confirm shift completion.
- o Resume commanded power operation.

A bilateral shift control scheme could accommodate unilateral shifts via repeat commands or restricted operations to prevent a damaging drive motor overspeed condition. A unilateral shift control scheme would independently control the gearbox shift status on each side, although the same protective algorithms would apply.

In the event of a mechanical failure of either shift mechanism, both gearboxes could be manually locked into either speed range to ensure continued, although reduced performance operation. The choice of speed range would be predicated on the tactical conditions at the time of the failure.

Shift controlling when the vehicle is operating at the shift point would be stabilized via the use of a hysteresis band to prevent shift "dithering." This band would be of variable width as a function of vehicle turning rate to accommodate the differential speeds within the rated-power speed range of the drive motors.

The inability of the electric drive motors of this concept to provide a rated-power speed band of sufficient width to satisfy vehicle mobility requirements mandates the inclusion of a two-speed gearbox. Although the addition of these gearboxes adds to the overall system complexity, they do not present any performance or control problems that cannot be satisfactorily addressed using state-of-the-art micro-processor control technology.

5.4.2.5 Final Drive

The final drive is a concentric, self-contained, heavy duty planetary gear set with a 4:1 reduction ratio. The output of the two speed gear box is input to the final drive at the planetary sun gear. The planetary ring gear is bolted to the final drive housing and is stationary. The planet carrier is coupled to the drive sprocket. The two speed gear box and final drive provide a total reduction of 65.5 in low and 21.86:1 in high. The pitch diameter of the drive sprockets is 24 inches.

5.4.3 Unique Mobility Configuration IV, Concept 2, 19.5 Ton Vehicle Application

The Unique Mobility concept IV-2 is a dual path drive system with separate mechanical and electric power paths that are combined at the two final drives by combining planetary gear sets. To achieve maximum tractive effort the mechanical path is decoupled and in lock-up for vehicle speeds from zero to 15 miles per hour and all tractive effort is provided solely by the electric

system. From 15 to 45 miles per hour the mechanical path is unlocked and coupled to the prime mover and propulsion effort is supplied by both the electric and mechanical path. The power split is controlled by the ECU via its regulation of the propulsion system generator and the prime mover. Figure 5.4-9 presents a schematic of the Unique Mobility concept IV-2.

The electric power path consists of an engine driven, permanent magnet AC generator whose output is rectified to DC and then inverted at controlled frequency to provide power to the permanent magnet traction motors. The traction motor output pinion gear drives the ring gear of the combining planetary at the final drive.

The mechanical path is an engine driven mechanical shaft which drives into the sun gear of the combining planetary at each final drive. A right angle and a cross drive gear box are used in the mechanical drive line to connect the transversely mounted engine to the final drives. The mechanical path also contains a clutch and brake to disconnect and lock up the mechanical shaft system when vehicle operation is in the zero to 15 mile per hour speed range. The mechanical cross shaft is used as a feed back path for transferring power from the inside sprocket to the outside sprocket during steer maneuvers.

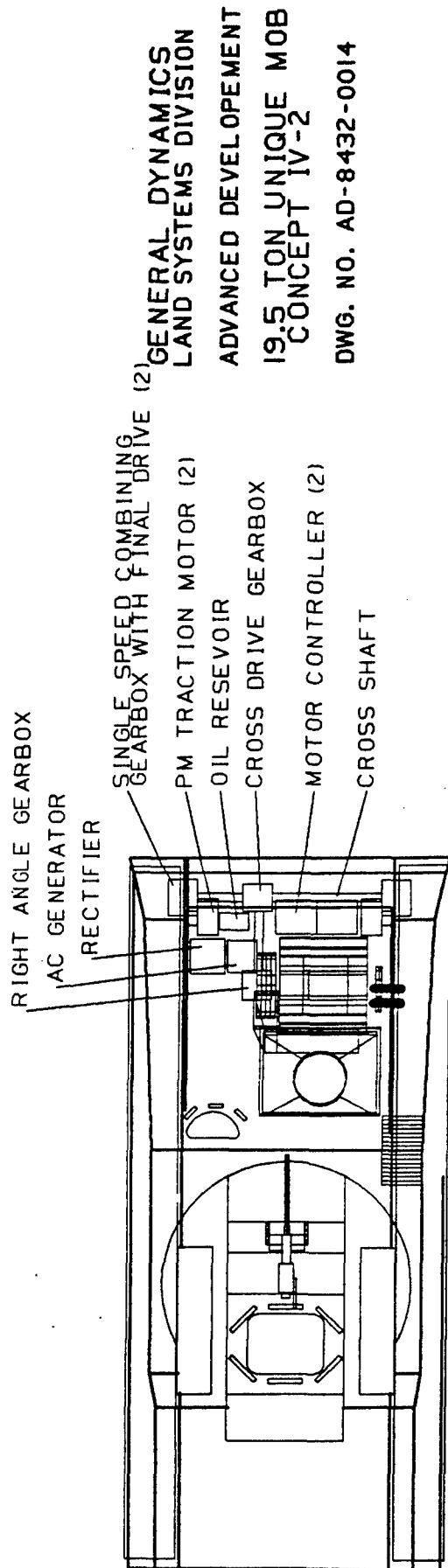
A summary of the physical characteristics for the Unique Mobility Transmission concept IV-2 for the 19.5 vehicle category is presented in table 5.4-3. A layout drawing of the Unique Mobility Dual Path concept installed in the 19.5 ton baseline vehicle with the cummins VTA-903T engine and other power pack subsystems is shown in figure 5.4-10.

The Unique Mobility concept has the highest technical risk of the three best electric drive concepts. The high technical risk is due chiefly to the traction motor design which is an early developmental, unconventional design. A 40 horsepower motor of this type was built in mid 1985 and is currently undergoing bench testing. The generator which is the same Garrett design used in the ACEC and Garrett concepts, has medium risk. The power conditioning units, the single speed combining gear boxes and other gear boxes are custom designs with low risk.

TABLE 5.4-3. UNIQUE MOBILITY CONCEPT IV-2 TRANSMISSION CHARACTERISTICS

VEHICLE GW 19.5 TON
CONF. IV
CONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 12		.56		103	417	93.5	18000 rpm
1	Rectifier	12 x 12 x 12		1.00		100	400	98	
2	Traction Motors	13 dia x 6.5	.50	1.00	110	220	192	96	10,000 rpm, Electric Shift, Air Cooled
2	Motor Controllers	12.8 x 12.8 x 12.8	1.20	2.40	75	150	210	98	
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case W/Clutch and Brake	10 x 10 x 12		.69		125		98	6.9:1 Ratio
2	Single Speed Com- bining Gearbox	14 dia x 8	.75	1.50	.80	160		98	Variable Ratio 4000 BUT/Min
2	Brakes		.20	.40		110			
1	Air & Oil Cooling System			3.00		200			Max Heat Rejection 3260 BUT/Min
1	Cross Drive Gearbox	12 x 12 x 12		1.00		120		98	
3	Shafts			.30		80			
	Connectors & Cables					30			
TOTAL:			<u>13.69</u>			<u>1438</u>		(82-91) 86 Avg.	



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19.5 TON UNIQUE MOB
CONCEPT IV-2
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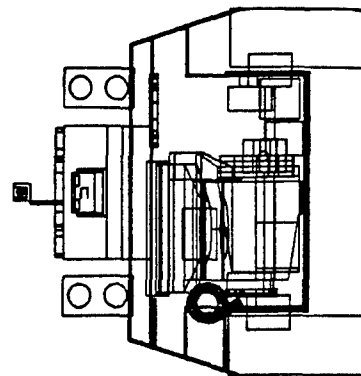
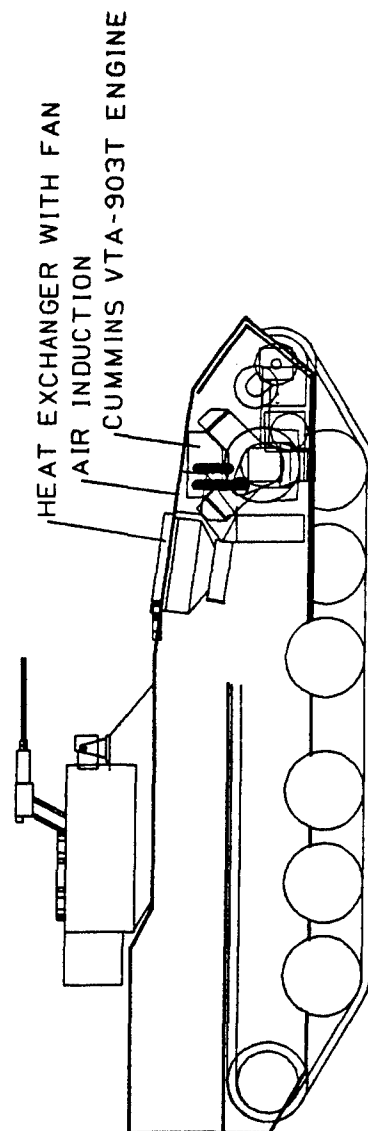


Figure 5.4-10. Unique Mobility Concept IV-2,
19.5 Ton Vehicle Installation

The PM traction motor uses rare earth Neodymium permanent magnets in the rotating field. This relatively new magnetic material offers a high magnetic energy product and has good mechanical strength. The potential for low cost magnets using this rare earth is good since the U.S. has adequate deposits of neodymium within its borders. The Neodymium magnet is sensitive to temperature and can lose magnetic strength at temperatures as low as 110°C. Close attention to the motor cooling design and the formulation of elements that make up the magnet can eliminate this potential problem.

The estimated production unit cost of the Unique Mobility concept based on a production run of 400 units is 145 K dollars. This includes the unit cost of components which make up the electrical and mechanical paths of this dual path concept. The cooling system and final drive costs are not included.

5.4.3.1 Generator

The AC generator is a Garrett, self-excited, brushless, oil cooled, permanent magnet machine rated at 400 horsepower. The generator uses rare earth cobalt permanent magnets to supply the field flux. The generator's rated speed is 18,000 RPM, which dictates the use of 6.9:1 ratio speed increase transfer case to raise the engine speed to the rated generator speed.

Generator Characteristics

Rating	370 KVA
Speed	18,000 RPM
Efficiency	93.5 percent
Voltage	685 Vrms Line to Line
Cooling	Oil Cooled

5.4.3.2 Rectifier

The rectifier is a phase delay rectifier. It performs two primary functions: Rectification of the input AC source (generator AC output) and regulation of current to the inverter. The rectifier operation is bilateral, enabling it to

receive and channel the reverse or regenerative power from the load (motor) to the input AC source (alternator). This is required for the dynamic braking. The rectifier unit contains voltage and current sensors which provide feedback signals to the ECU. Figure 5.4-3 shows the rectifier bridge.

Rectifier Characteristics

Rating	370 KVA
Efficiency	98%
Voltage	685 Vdc
Current	410 DC AMPS
Cooling	Oil Cooled

5.4.3.3 Inverter

The inverter consists of an inductor filter and a six pulse transistor inverter bridge. The inverter performs the commutation function for the AC traction motors. The inverter is a line commutated type, whereby the transistors are turned off by the back emf of the motor(s). The inverter unit operation is bilateral and is fed from a DC bus. Figure 5.4-11 shows the inverter schematic.

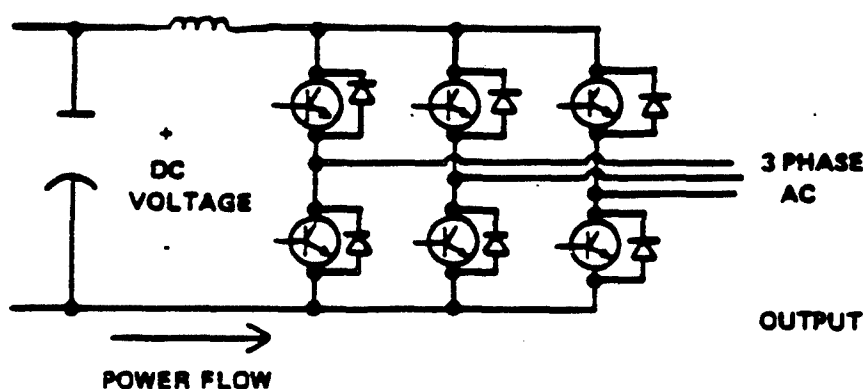


Figure 5.4-11. Transistor Inverter Schematic

Inverter Characteristics

Efficiency	96%
Voltage	284 Vac
Current	410 AMPS
Cooling	Oil Cooled

5.4.3.4 Traction Motor

The Unique Mobility Traction motor is a self-synchronous, air-cooled, permanent magnet AC machine. The rotor is constructed from two thin wall hollow cylinders mounted concentrically on the motor shaft. The stator, also a thin wall cylinder, is centered between the two rotor cylinders thus forming two radial air gaps - one between the stator and the outside rotor cylinder, and one between the stator and the inside rotor cylinder. Radially oriented neodymium iron boron permanent magnets are mounted on both the inside and the outside rotor cylinders. Figure 5.4-12 shows the rotor and stator arrangement of the Unique Mobility Motor Design.

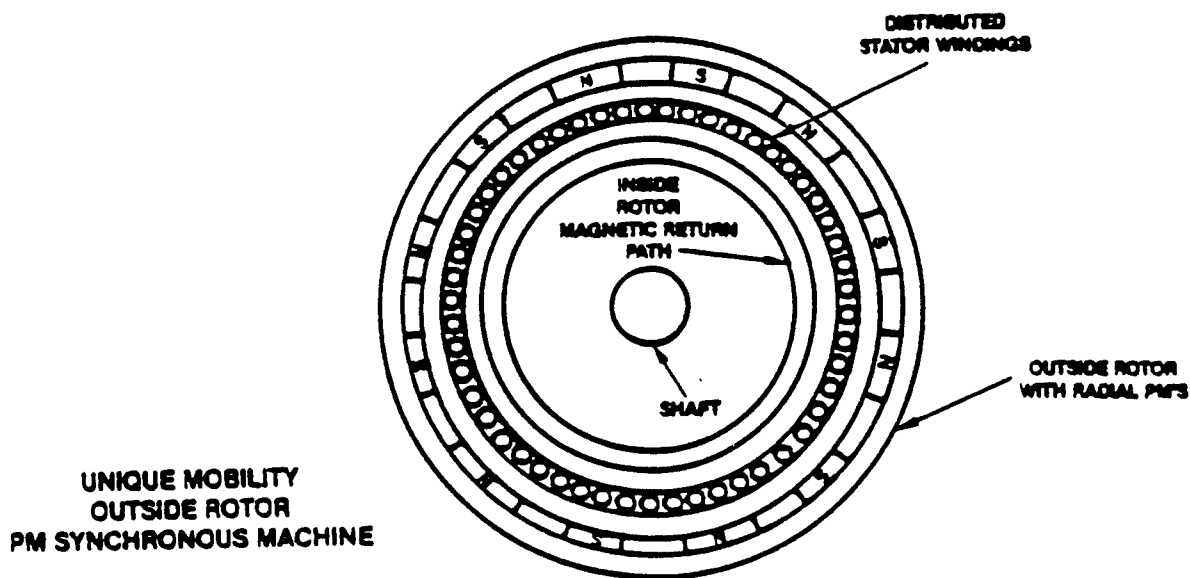


Figure 5.4-12. Unique Mobility Traction Motor Cross Section

The thin wall construction of the rotor and stator and the minimal amount of magnetic material used, results in an easily cooled high power density motor design. Regarding intermittent duty, the motor can deliver a maximum of two times rated power for up to 30 seconds.

The motor stator consists of a multi-phase, axially directed power windings and radially oriented magnetic material to enhance magnetic flux production. The windings and magnetic material are supported and contained by the fiber reinforced composite stator structure.

The three phase stator windings have four windings per phase which can be connected in three different configurations to give three different speed ranges. By switching from one winding configuration to another winding configuration, referred to as an electric shift, a 9 to 1 constant power speed range is produced by a motor design that is relatively small and lightweight. This is significant in that the requirement for a shifting gearbox is eliminated.

Two relay switches are used to connect the windings in the three different configurations. Power on the windings is momentarily dropped during switching to avoid arcing. The motor speed ranges and associated winding configurations are:

<u>Speed Range</u>	<u>Winding Configuration</u>
0-2,500 RPM	All in series
0-5,000 RPM	Two in series Two in parallel
0-10,000 RPM	All in parallel

The Unique Mobility motor rated torque and efficiency characteristics are shown in figure 5.4-13.

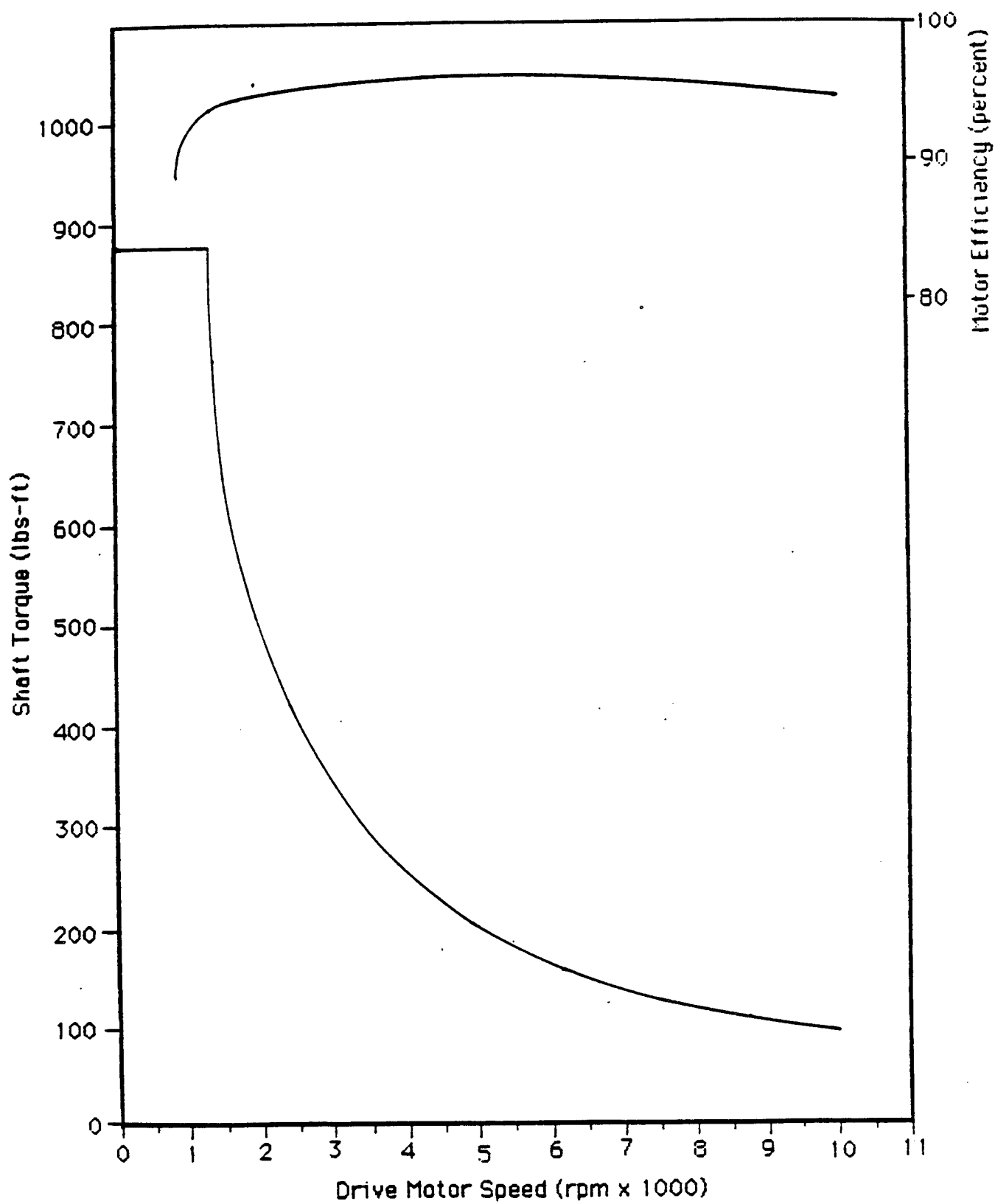


Figure 5.4-13. Torque and Efficiency Versus Speed
for 192 Horsepower Unique Mobility PM Motor

5.4.3.5 Final Drives and Gearboxes

The final drive units consist of two planetary gear sets. The first planetary set, which is a combining gear set, integrates the mechanical path input at the sun gear and the electric path input at the ring gear. The output carrier of the first planetary stage is connected to the input sun gear of the second planetary gear set. The output carrier of the second planetary is coupled to the drive sprocket. The second planetary is a fixed 4:1 reduction ratio while the combining planetary is variable ratio reduction when both inputs (sun and ring) are in use and is a fixed 1.33:1 reduction ratio when the mechanical path is in lockup. Due to the 3:1 reduction provided by the traction motor pinion gear on the ring gear of the combining planetary, the total reduction between the motor output and the sprocket is 16:1 when the mechanical path is in lockup. The total reduction is variable when both mechanical and electrical paths are operative and is dependent on the speed of each.

A right angle gear box and a cross drive gear box are required in the mechanical drive line between the engine output and the final drive input. These gear boxes use bevel spur gears and their function is solely to change direction of the mechanical path; consequently they are conceived with 1:1 ratios.

5.4.4 Garret Configuration I, Concept 3, 40 Ton Vehicle Application

The Garrett Concept I-3 for the 40 ton vehicle application is the same as the Garrett Concept I-10 for the 19.5 ton vehicle application (see section 5.4.2), except that the concept has been scaled up to satisfy the 40 ton vehicle requirements and the power plant is based on the AD1000 engine.

A schematic of the Garrett concept I-3 for the 40.0 ton vehicle category is presented in figure 5.4-14. Table 5.4-4 presents a summary of the transmission characteristics for concept I-3. A layout drawing of the Garrett concept installed in the 40 ton baseline vehicle with the AD1000 engine and other power pack subsystems is shown in figure 5.4-15.

The Garrett concept for the 40 ton application is considered to have medium technical risk for the same reasons given for 19.5 ton Garrett concept.

**GARRETT
SCHEMATIC**

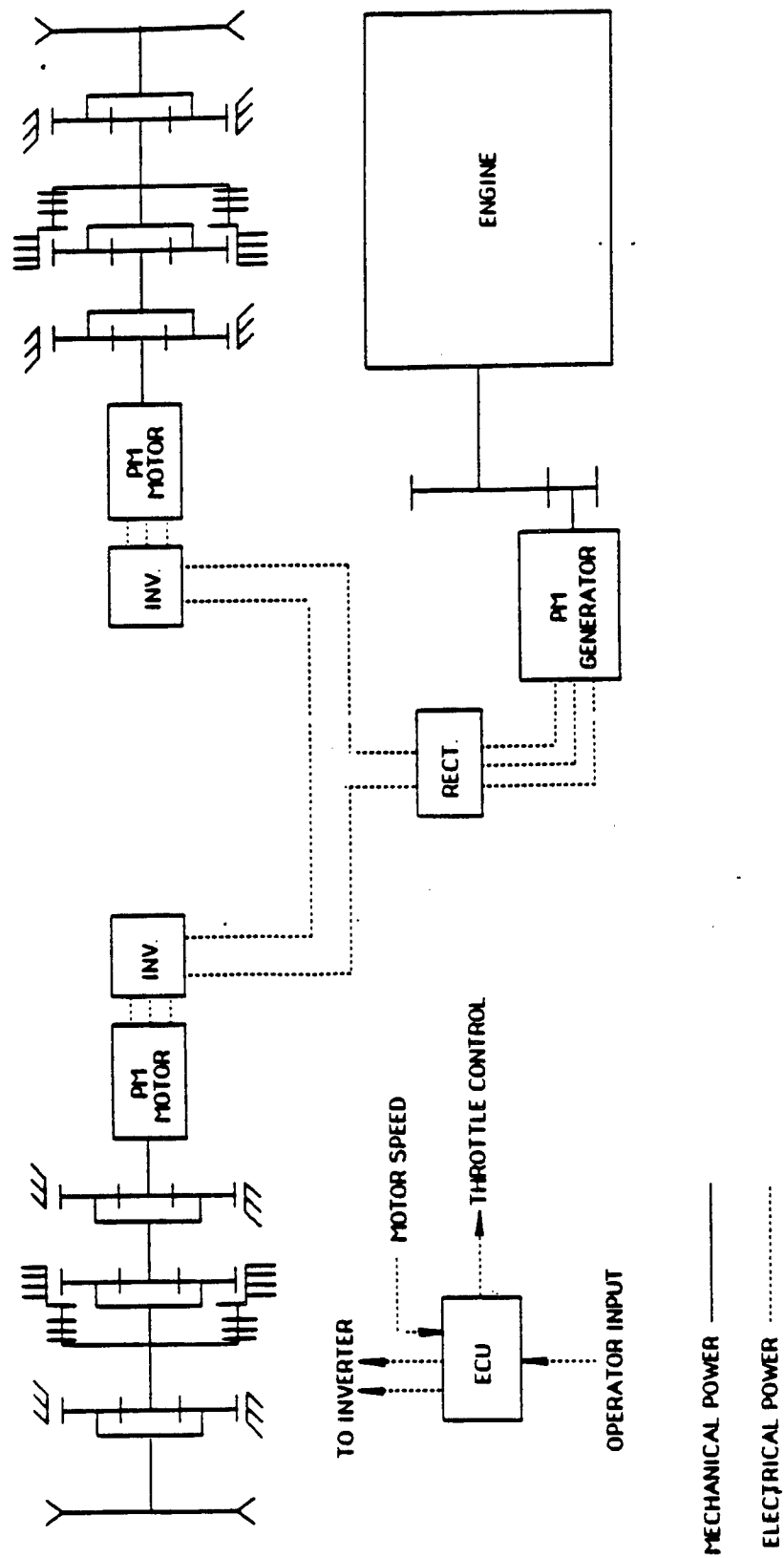


Figure 5.4-14. Garrett Concept I-3, 40 Ton, Schematic

TABLE 5.4-4. GARRETT CONCEPT I-3 TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON
CONF. I
CONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 15.8		.90		230	890	94.5	18000 rpm
3	PCU	13.2 x 13.2 x 13.2		4.00		400	426	96	
2	Traction Motor	13.5 dia x 20	1.66	3.32	525	1050	388	94-88	4500, 18500 rpm
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 7.3		.65		158		98	6.9:1 Ratio
2	2 Speed Gearbox	14 dia x 13.5	1.20	2.40	80	160		98-96	
1	Oil Cooling System			4.20		480			Max Heat Rejection 8330 BUT/Min
2	Brakes		.2	.40	110	220			
	Connectors & Cables					50			
TOTAL:			16.7			2788		79 avg. (78-81)	

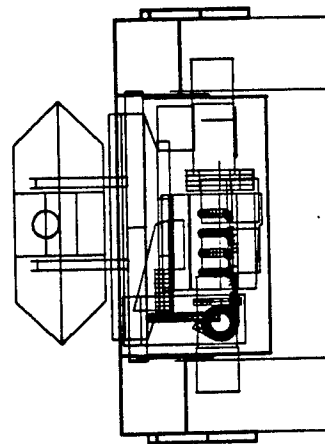
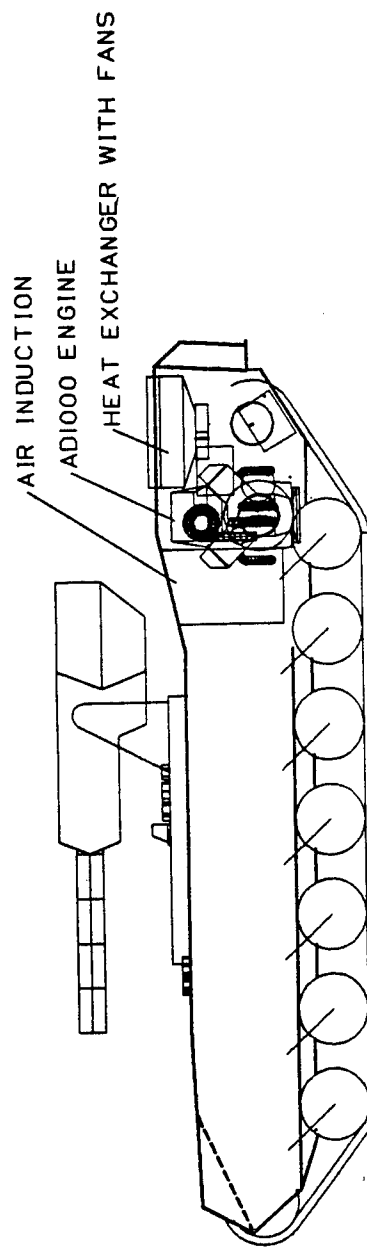
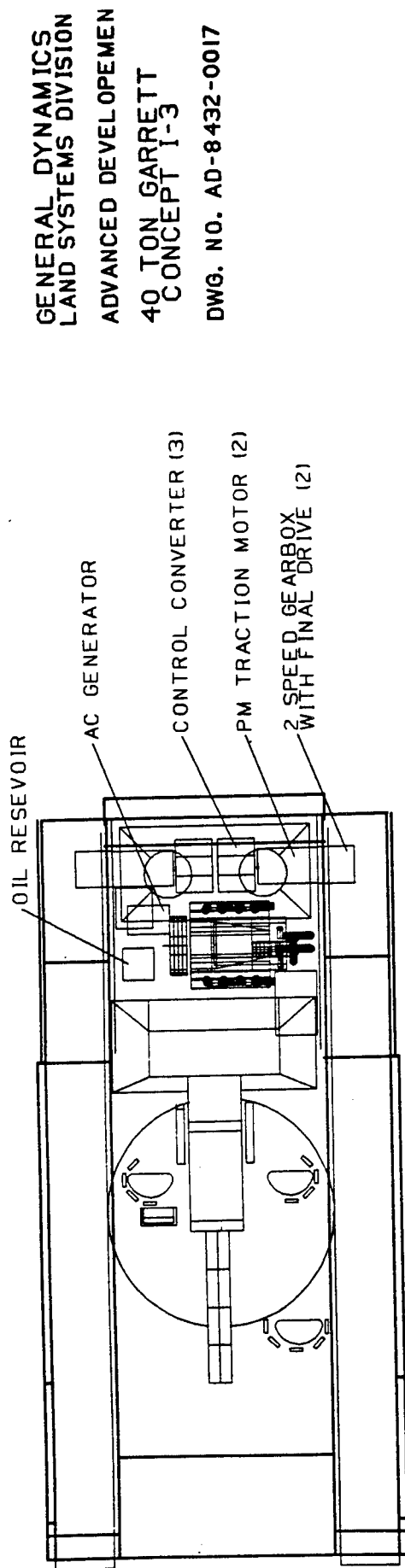


Figure 5.4-15. Garret Concept I-3 40 Ton Vehicle Installation

The production unit cost of the 40 ton Garrett Electric transmission concept is estimated at 240 K dollars based on a production of 400 units.

The major characteristics of the electrical machinery and the power conditioning equipment used in the Garrett Concept I-3 are now presented. The rated torque and efficiency characteristics of the Garrett 384 horsepower PM traction motor are given in figure 5.4-16.

Generator Characteristics

Rating	740 KVA
Speed	18,000 RPM
Efficiency	94.5%
Voltage	747 Vrms Line to Line
Cooling	Oil Cooled

Rectifier Characteristics

Rating	740 KVA
Efficiency	98%
Voltage	747 Vdc
Current	734 DC AMPS
Cooling	Oil Cooled

Inverter Characteristics

Efficiency	96%
Voltage	310 Vac
Current	734 AMPS
Cooling	Oil Cooled

Traction Motor Characteristics

Rating	384 HP
Efficiency	94% at Base Speed
Base Speed	4,600 RPM

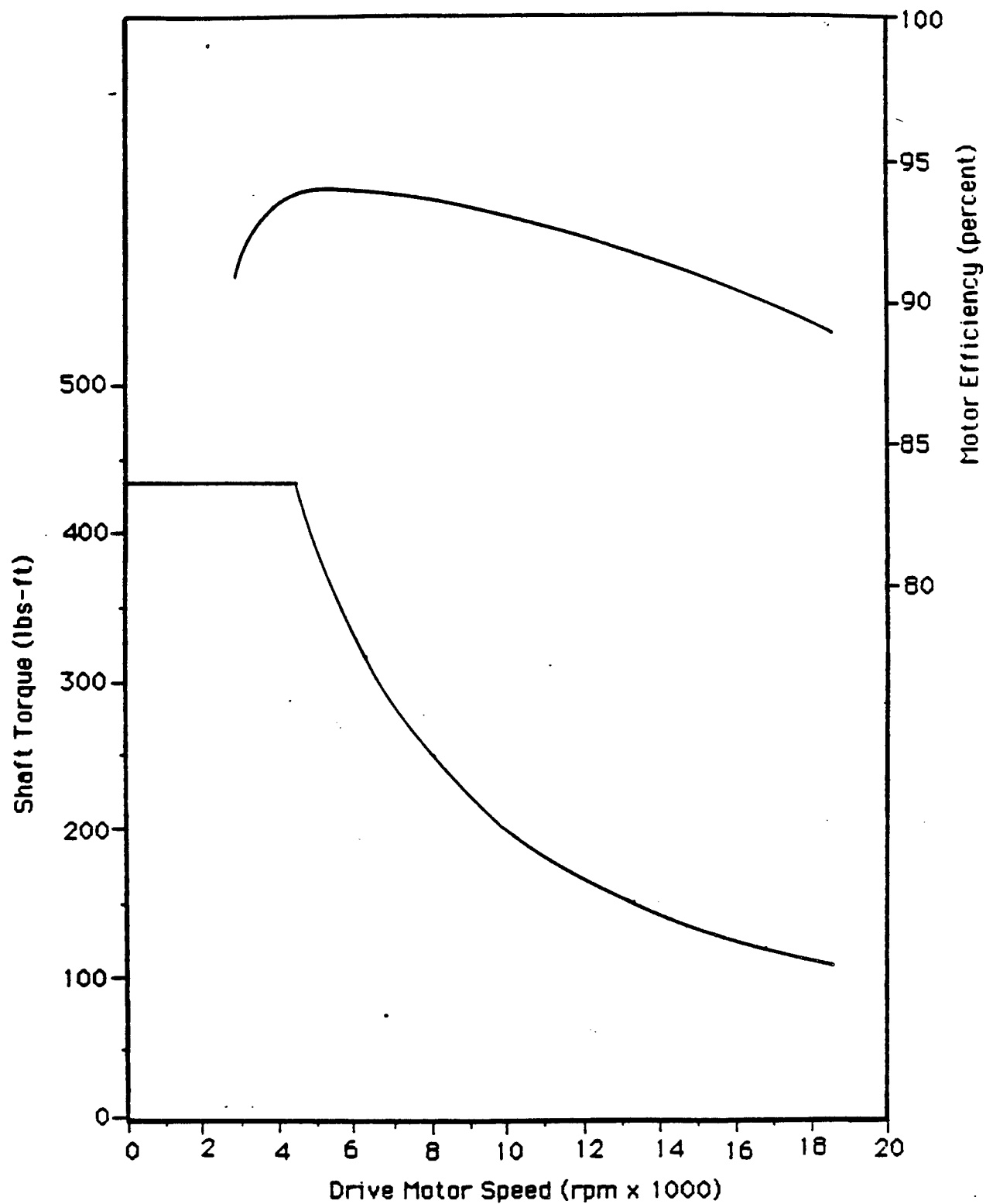


Figure 5.4-16. Torque and Efficiency Versus Speed
for 384 Horsepower Garrett PM Motor

Traction Motor Characteristics

(Continued)

Max. Rated Speed	18,500 RPM
Voltage	310 Vrms Line to Line
Cooling	Oil Cooled

5.4.5 Unique Mobility Configuration IV, Concept 2, 40 Ton Vehicle Application

The Unique Mobility concept IV-2 for the 40 ton vehicle application is the same as the Unique Mobility concept IV-2 for the 19.5 ton vehicle application (see section 5.4.3), except that the concept has been up rated to satisfy the 40 ton vehicle performance requirements and the prime mover used is the AD1000 engine. Also two 192 horsepower traction motors are used at each final drive rather than a single 384 horsepower motor.

A schematic of the Unique Mobility concept IV-2 for the 40 ton vehicle category is presented in figure 5.4-17. Table 5.4-5 presents a summary of the transmission characteristics for concept I-3. A layout drawing of the Unique Mobility concept installed in the 40 ton baseline vehicle with the AD1000 engine and other power pack subsystems is shown in figure 5.4-18.

The Unique Mobility concept IV-2 for the 40 ton vehicle application has high technical risk for the same reasons given for the 19.5 ton Unique Mobility concept.

The production unit cost of the Unique Mobility electric transmission for 40 ton vehicle application is estimated at 215 K dollars based on 400 production units.

The major characteristics of the electrical machinery and the power conditioning equipment used in the Unique Mobility concept IV-2 is now presented.

UNIQUE MOBILITY 40.0 TON SCHEMATIC

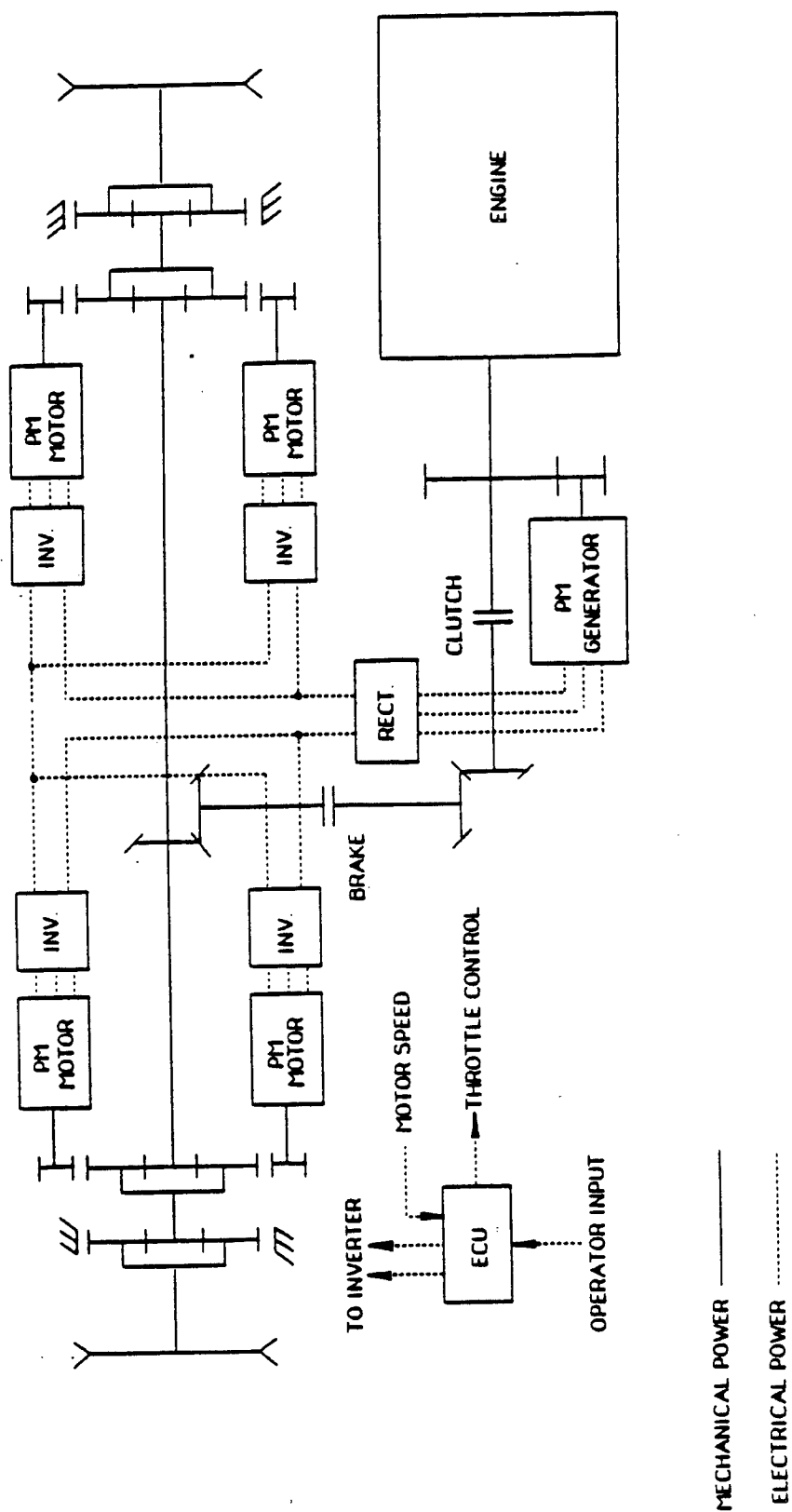


Figure 5.4-17. Unique Mobility Concept IV-2, 40 Ton, Schematic

Generator Characteristics

Rating	740 KVA
Speed	18,000 RPM
Efficiency	94.5%
Voltage	685 Vrms Line to Line
Cooling	Oil Cooled

Rectifier Characteristics

Rating	740 KVA
Efficiency	98%
Voltage	685 Vdc
Current	820 DC AMPS
Cooling	Oil Cooled

Inverter Characteristics

Efficiency	96%
Voltage	284 Vac
Current	410 AMPS
Cooling	Oil Cooled

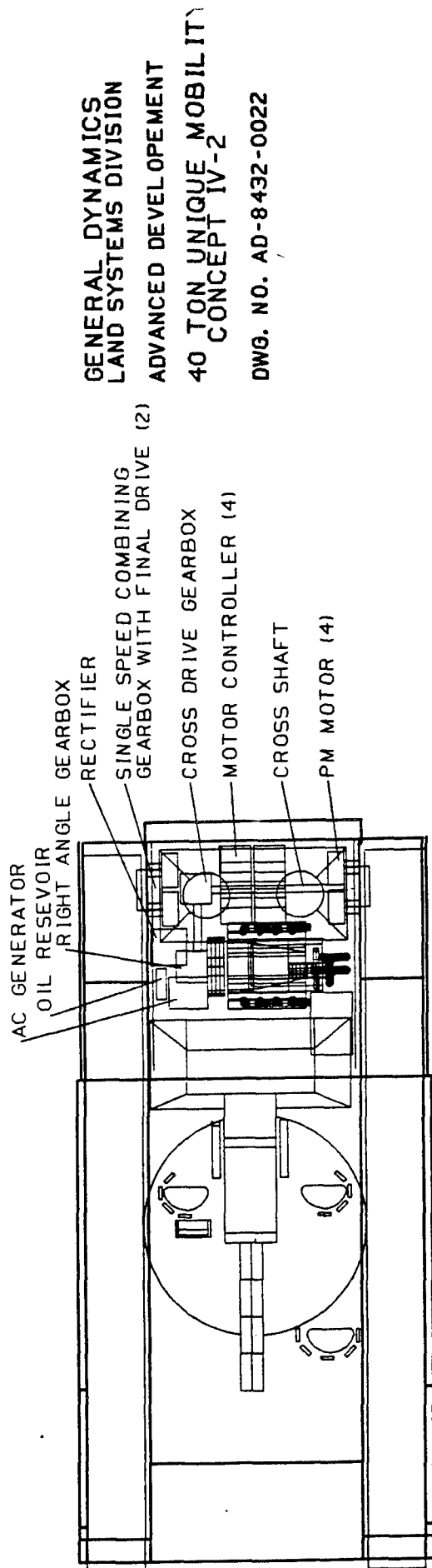
Traction Motor Characteristics

Rating	192 HP
Efficiency	96%
Base Speed	1100, 2500, 5000 RPM
Max. Rated Speed	10,000 RPM
Voltage	284 Vrms Line to Line
Cooling	Air Cooled

TABLE 5.4-5. UNIQUE MOBILITY CONCEPT IV-2 TRANSMISSION CHARACTERISTICS

VEHICLE GW 40 TON
CONF. IV
CONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 15.1		.86		217	837	94.5	18000 rpm
1	Rectifier	14.5 x 14.5 x 14.5		1.75		180		98	Oil Cooled
4	Motor Controller	12.8 x 12.8 x 12.8	1.20	4.80	75	300	210	98	Oil Cooled
4	Traction Motor	13 dia x 6.5	.50	2.00	110	440	192	94	Elec Shift Air Air Cooled
1	Single Speed Com- bining Gearbox	14 dia x 8	.75	1.50	100	200			Variable Ratio
1	ECU	12 x 10 x 12		.80		40			
1	Transfer Case W/Clutch and Brake	12 x 12 x 12		1.00		180		98	5.6:1 Ratio
1	Cross Drive Gearbox	12 x 12 x 12		1.00		150		98	
1	Air & Oil Cooling System			4.00		250			
3	Shafts			.40		60			
2	Brakes		.40	.80	110	220			
	Connectors & Cables					40			
TOTAL:				<u>18.91</u>		<u>2277</u>		85 avg. (82-88)	



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40 TON UNIQUE MOBILITY
CONCEPT IV-2
DWG. NO. AD-8432-0022

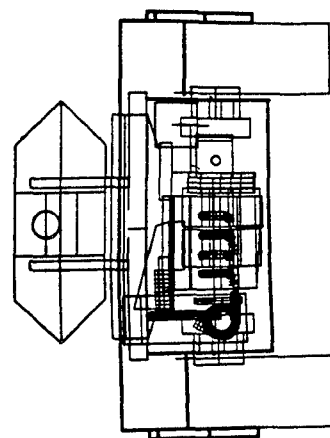
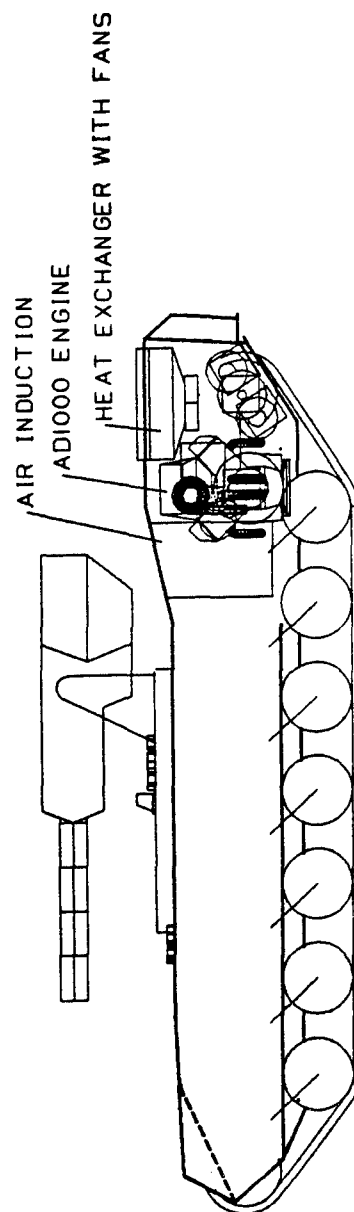


Figure 5.4-18. Unique Mobility Concept IV-2, 40 Ton Vehicle Installation

5.4.6 Efficiency

The efficiency of the best three electric transmission concepts is presented in figures 5.4-19 through 5.4-23 for the 19.5 and 40 ton vehicle applications. The efficiency is given for full load conditions over the vehicle speed range (zero to 45 miles per hour). The data of figures 5.4-19 through 5.4-23 represents the integrated efficiencies of all transmission components from the engine output to (but not including) the last planetary gear set of the final drive. The average efficiencies of the best three electric transmission concepts over 90 percent of the vehicle speed range are listed below:

19.5 ton ACEC concept I-5	83%
19.5 ton Garret concept I-10	78%
19.5 ton Unique Mobility concept IV-2	87%
40 ton Garrett concept I-3	79%
40 ton Unique Mobility concept IV-2	88%

The relatively low efficiency of the Garrett concept is due mainly to the power conditioning required for this AC system. The high efficiency of the Unique Mobility concept is attributed to the efficient-mechanical path of this dual path configuration.

5.4.7 Speed of System Gear Elements

This section discusses and presents the speeds of electric Drive system gear elements when the vehicle is operated at full throttle in the propulsion and steer modes. The speeds of system elements were determined for the best electric drive concepts over the output speed range of the vehicle in 100 rpm increments. Engine speed was assumed constant at the maximum speeds of 2,600 rpm (VTA 903T) and 3,200 rpm (AD1000) for the 19.5 ton and 40 ton vehicle concepts respectively. Element speeds were also determined at the 5 mph and 15 mph shift points because these were of interest. Drive sprocket speed was used as the starting point for determining the element speed values for each drivetrain concept.

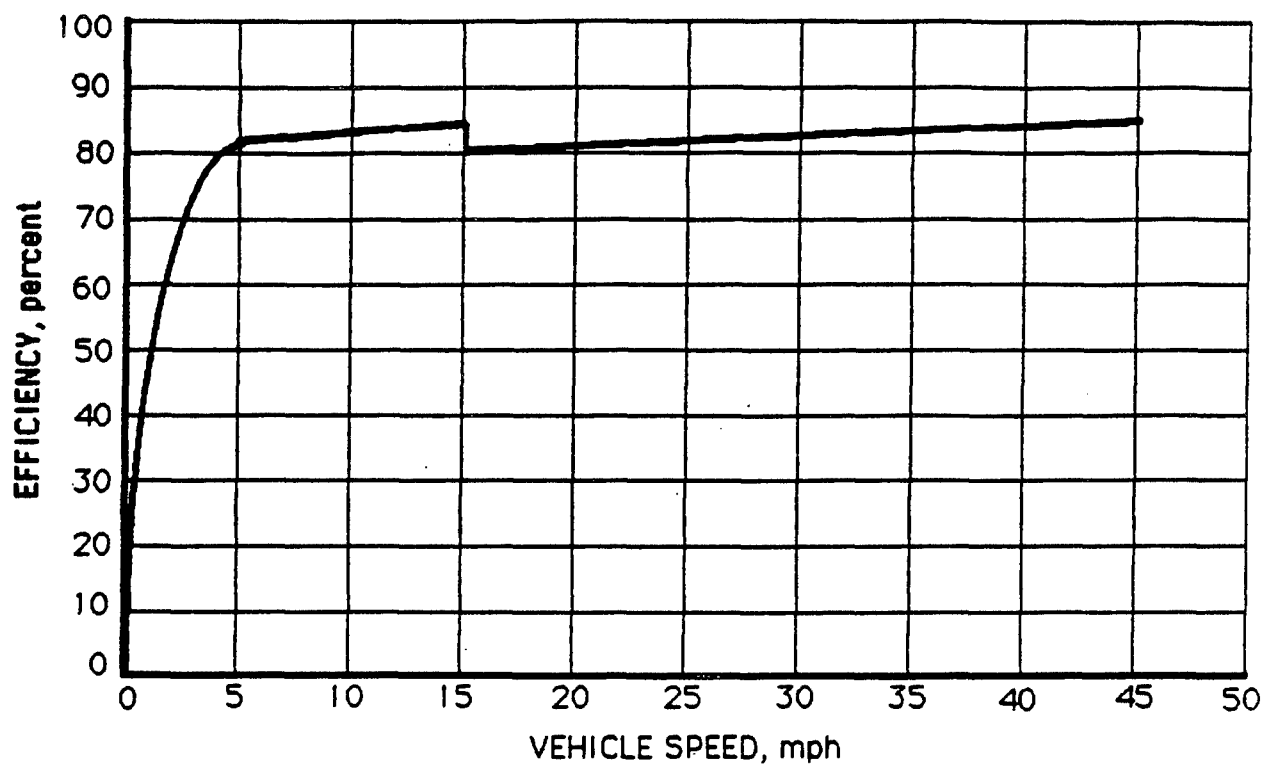


Figure 5.4-19. Efficiency of 19.5 Ton ACEC Concept I-5

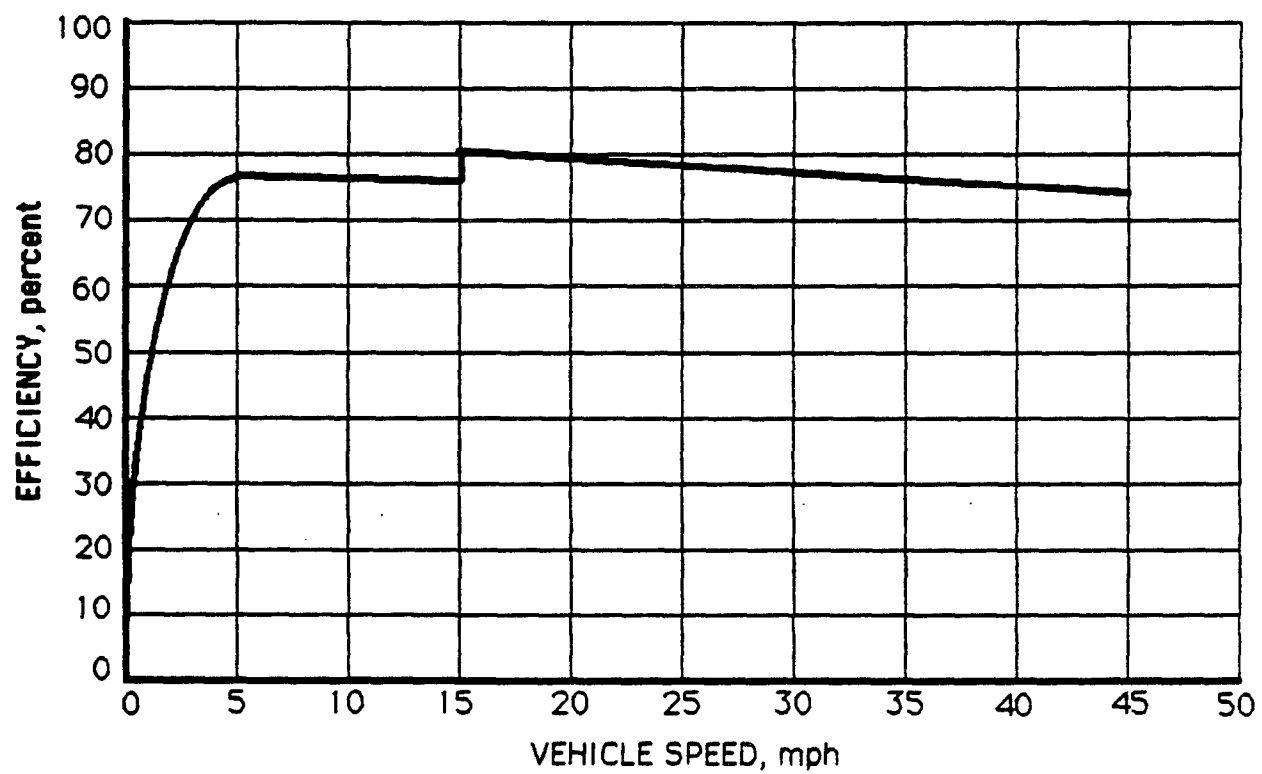


Figure 5.4-20. Efficiency of 19.5 Ton Garrett Concept I-10

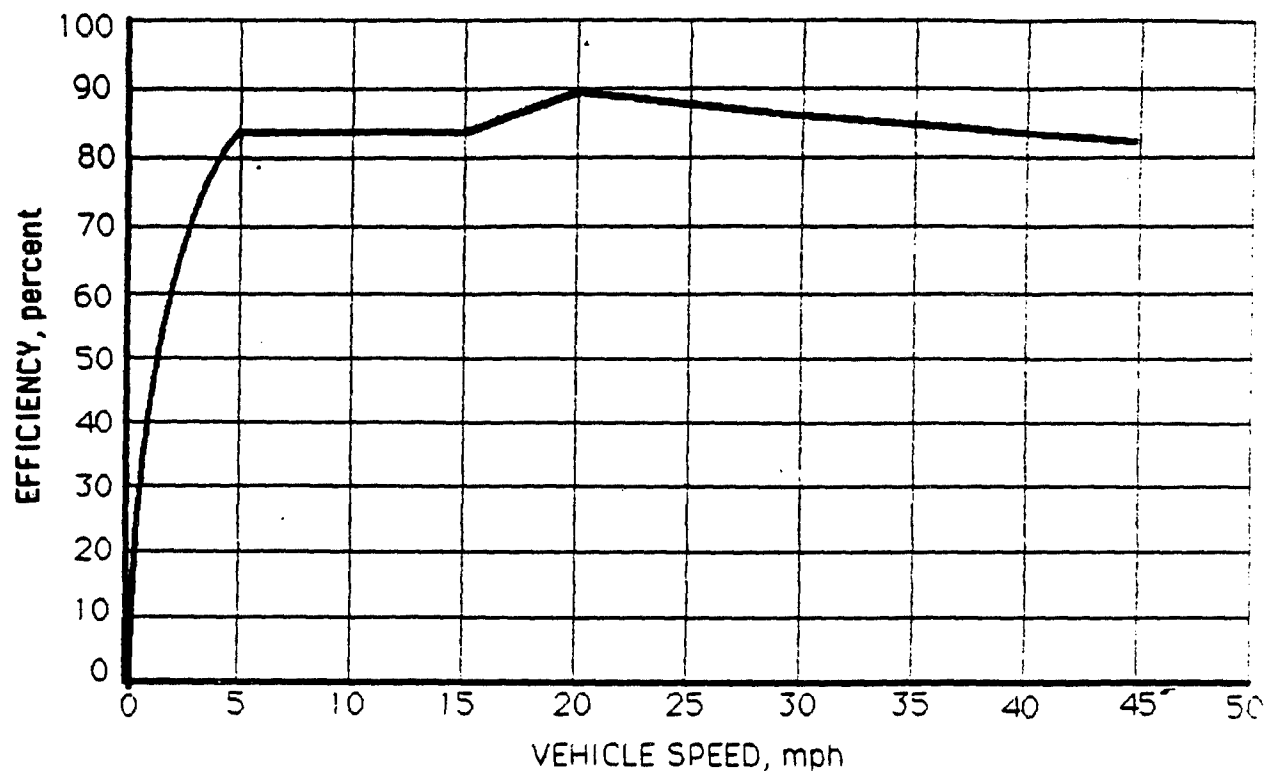


Figure 5.4-21. Efficiency of 19.5 Ton Unique Mobility Concept IV-2

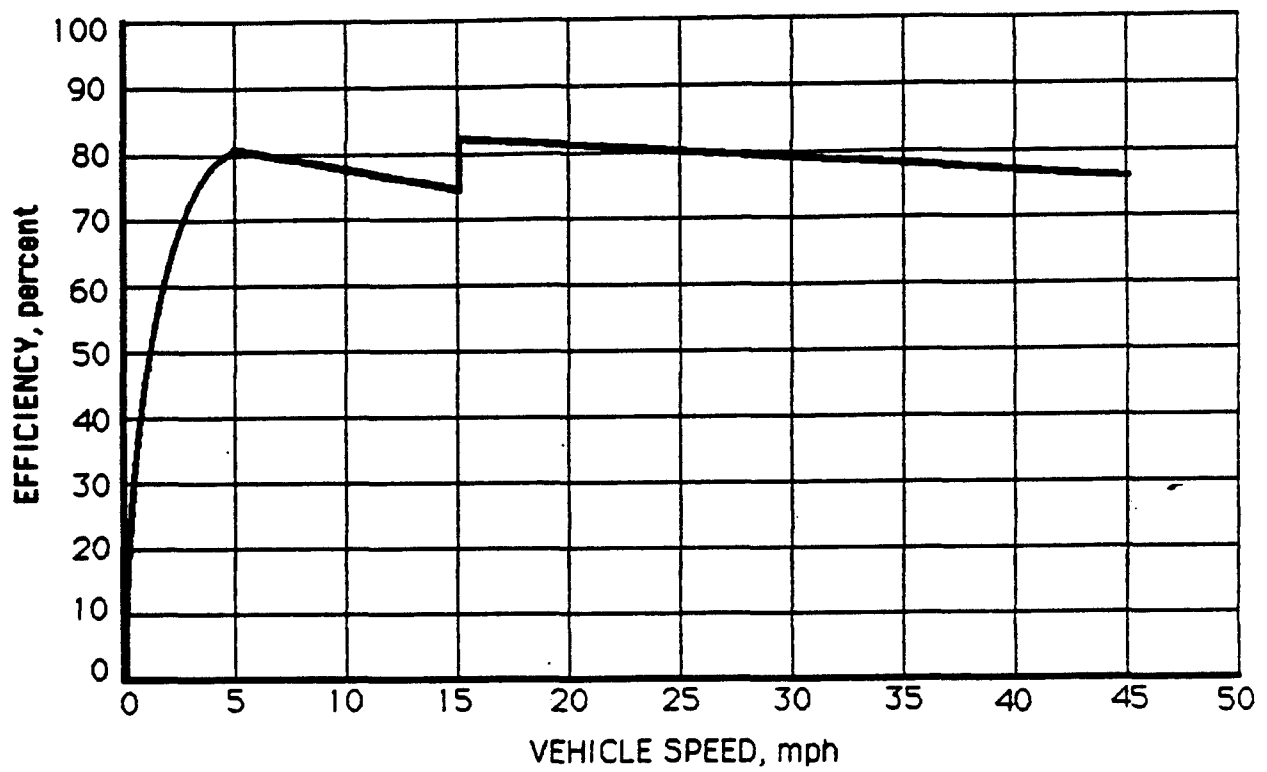


Figure 5.4-22. Efficiency of 40 Ton Garret Concept I-3

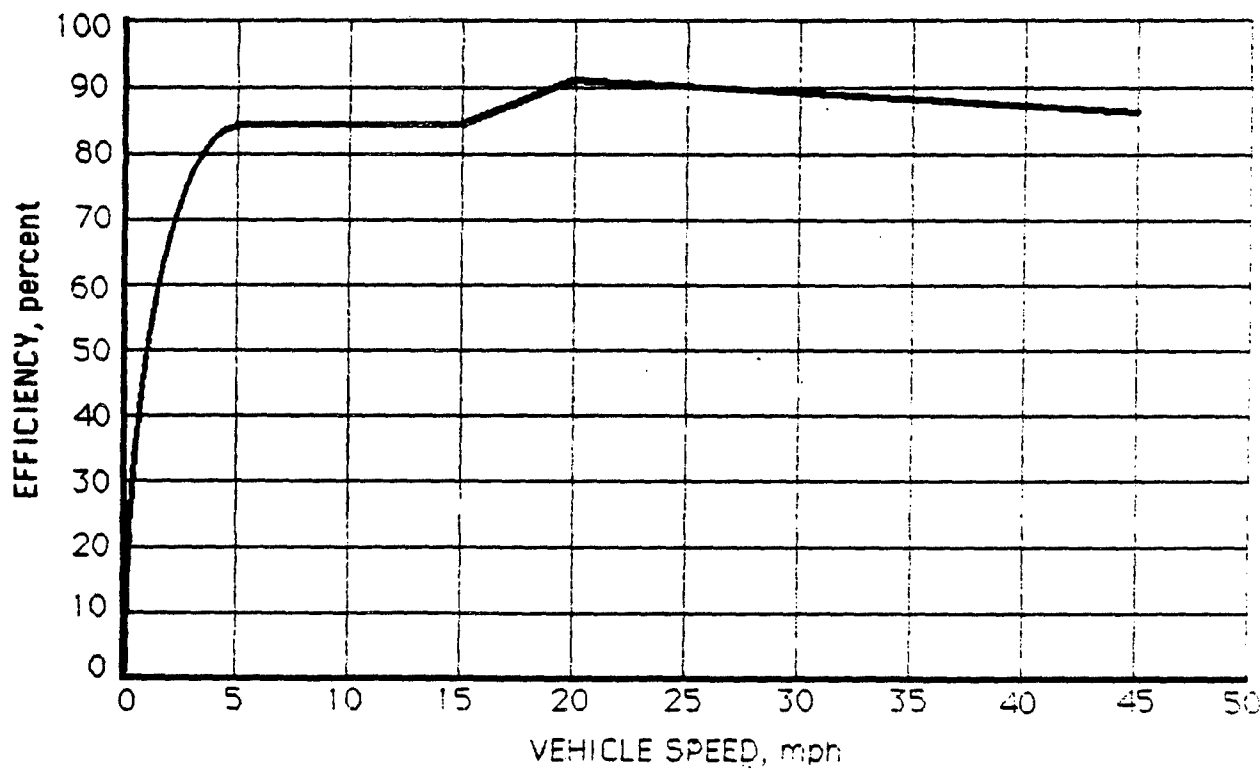


Figure 5.4-23. Efficiency of 40 Ton Unique Mobility Concept IV-2

During propulsion, the speed of the connected electric drive gear elements determines the output sprocket speed. Hence, the sprocket speed at a particular vehicle speed can be used to find each element speed by a back calculation from the sprocket to the engine output shaft. This method is proper because in the electric drivetrain it is the gear meshes that transfer engine power to the track. A fundamental property of these gear meshes is that speed and/or torque is transferred as a ratio of gear diameters involved in a mesh. In non-mathematical form, this principle is stated in the Machinery's Handbook (21st Edition) as follows:

$$\frac{\text{Speed of Driver}}{\text{Speed of Idler}} = \frac{\text{Diameter of Idler}}{\text{Diameter of Driver}}$$

This relationship formed the calculation basis for determining the speed of simple drivetrain elements. The speed of planetary gear elements were determined by the relationship:

$$N_1 = i_o N_2 + (1 + i_o) N_c$$

Where

$$N_1 = \text{Speed of Sun Gear}$$

$$N_2 = \text{Speed of Ring Gear}$$

$$N_c = \text{Speed of Planet Carrier}$$

$$i_o = \frac{N_1}{N_2} = \text{Basic Speed Ratio (carrier shaft locked)}$$

Element speed in a maximum steer situation is found essentially the same as described above, but with the exception that the inside and outside drive sprocket speeds must be different to produce skid steering. This is necessary because in skid steering the outside track must travel a greater distance than the inside track and accomplish this in the same time period if a controlled turn is to be realized. To find the velocity of each track, the following equations were taken from ATAC Technical Report No. 10969:

$$\begin{aligned}
 V_o &= V_s + \Delta V/2 \\
 V_I &= V_s - \Delta V/2 \\
 \Delta V &= \frac{(T + BL)}{12R} V_s
 \end{aligned}$$

Where:

V_o = velocity of outside track (mph)
 V_I = velocity of inside track (mph)
 V_s = linear vehicle velocity (mph)
 ΔV = velocity difference (mph)
 B = known constant (depends on vehicle)
 L = track length (in)
 T = track spread (in)
 R = radius of turn (ft)

Once the inside and outside track velocities are computed from these equations, the respective drive sprocket speed can be found by dividing track velocity by drive sprocket radius. The calculation of the system element speeds in the maximum steer case is identical to that already described for the straight ahead, (i.e., no turning).

5.4.7.1 19.5 Ton V Speed Tables

Element speed values were computed for each of the 19.5 ton drivetrain concepts under straight ahead and maximum steer conditions by the method described in the previous section. Table 5.4-6 shows an element speed summary for the ACEC concept (I-5) in the straight ahead mode.

Operational details of the ACEC concept are discussed in section 5.4.1. Table 5.4-7 shows an element speed summary for this concept under maximum steer condition.

Table 5.4-8 shows the element speed summary for the Garrett concept (I-10) in the straight ahead mode. Operational details of the Garrett concept are discussed in section 5.4.2.

5.4.7.2 40 Ton Speed Tables

Element speed values were also computed for each of the two 40 ton drivetrain concepts using the methodology previously described for the 19.5 ton concepts. A maximum engine speed of 3200 rpm is required for this heavier vehicle. The element speed tables for the Garrett and Unique Mobility 40 ton concepts are presented in Tables 5.4-12 thru 5.4-15.

TABLE 5.4-6. ELEMENT SPEED SUMMARY FOR MOTOR THRU FINAL DRIVE IN RPM

19.5 TON ACEC (I-5)

VEHICLE SPEED MPH	(24 DIA) SPROCKET	CARRIER	FINAL DRIVE (3.5 DIA) SUN	TWO SPEED GEARBOX							MOTOR
				(10.5 DIA) RING	CARRIER	PLANETARY GEAR		OFFSET GEAR			
						(3.0 DIA) SUN	(6.0 DIA) RING	(7.85 DIA) IDLER	(3.5 DIA) PINION		
0	0	0	0	0	0	0	0	0	0	0	
5	70	70	280	0	280	840	0	840	-1884	-1884	
7	100	100	400	0	400	1200	0	1200	-2692	2692	
14	200	200	800	0	800	2400	0	2400	-5383	-5383	
15	210	210	840	0	840	2520	0	2520	-5652	-5652	
*15	210	210	840	0	840	840	840	840	-1884	-1884	
21	300	300	1200	0	1200	1200	1200	1200	-2692	-2692	
28	400	400	1600	0	1600	1600	1600	1600	-3589	-3589	
35	500	500	2000	0	2000	2000	2000	2000	-4486	-4486	
42	600	600	2400	0	2400	2400	2400	2400	-5383	-5383	
45	630	630	2520	0	2520	2520	2520	2520	-5652	-5652	

*Drivetrain shifted to high gear

TABLE 5.4-7. ELEMENT SPEED SUMMARY AT MAXIMUM STEER FOR
MOTOR THRU FINAL DRIVE IN RPM

VEHICLE SPEED MPH	AVG. SPROCKET	MIN RADIUS FT	TRACK	SPROCKET	CARRIER	19.5 TON ACEC (I-5)									
						FINAL DRIVE		PLANETARY GEAR				TWO SPEED GEARBOX			
						SUN	RING	CARRIER	SUN	RING	(3 0 DIA)	IDLER	(7.85 DIA)	PINION	MOTOR
Pivot	0	N/A	Outside	27	27	108	0	108	324	0	0	324	-727	-727	-727
			Inside	-27	-27	-108	0	-108	-324	0	0	-324	727	727	727
7	100	8	Outside	175	175	700	0	700	2100	0	0	2100	-4710	-4710	-4710
			Inside	26	26	104	0	104	312	0	0	312	-700	-700	-700
14	200	22	Outside	256	256	1024	0	1024	3072	0	0	3072	-6890	-6890	-6890
			Inside	145	145	580	0	580	1740	0	0	1740	-3902	-3902	-3902
*21	300	43	Outside	343	343	1372	0	1372	1372	1372	1372	1372	-3077	-3077	-3077
			Inside	257	257	1028	0	1028	1028	1028	1028	1028	-2306	-2306	-2306
28	400	77	Outside	433	433	1732	0	1732	1732	1732	1732	1732	-3885	-3885	-3885
			Inside	368	368	1472	0	1472	1472	1472	1472	1472	-3302	-3302	-3302
35	500	121	Outside	526	526	2104	0	2104	2104	2104	2104	2104	-4719	-4719	-4719
			Inside	475	475	1200	0	1200	1900	1900	1900	1900	-4262	-4262	-4262
42	600	175	Outside	579	579	2488	0	2488	2488	2488	2488	2488	-5580	-5580	-5580
			Inside	622	622	2316	0	2316	2316	2316	2316	2316	-5195	-5195	-5195
45	630	193	Outside	651	651	2604	0	2604	2604	2604	2604	2604	-5840	-5840	-5840
			Inside	610	610	2400	0	2400	2440	2440	2440	2440	-5472	-5472	-5472

*Drivetrain shifted to high gear at 15 mph.

TABLE 5.4-8. ELEMENT SPEED SUMMARY FOR MOTOR THRU FINAL DRIVE IN RPM

19.5 TON GARRETT (I-10)

VEHICLE SPEED (24 DIA) MPH	SPROCKET	FINAL DRIVE (3.5 DIA)		TWO SPEED GEARBOX									
				SECOND PLANETARY					FIRST PLANETARY				
				CARRIER	SUN	(3.0 DIA)	(6.0 DIA)	CARRIER	SUN	(1.5 DIA)	(6.7 DIA)	RING	MOTOR
0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	70	70	280	280	840	840	0	840	4600	4600	0	0	4600
7	100	100	400	400	1200	1200	0	1200	6570	6570	0	0	6570
14	200	200	800	800	2400	2400	0	2400	13140	13140	0	0	13140
15	210	210	840	840	2520	2520	0	2520	13797	13797	0	0	13797
*15	210	210	840	840	840	840	840	840	4600	4600	0	0	4600
21	300	300	1200	1200	1200	1200	1200	1200	6570	6570	0	0	6570
28	400	400	1600	1600	1600	1600	1600	1600	8760	8760	0	0	8760
35	500	500	2000	2000	2000	2000	2000	2000	10950	10950	0	0	10950
42	600	600	2400	2400	2400	2400	2400	2400	13140	13140	0	0	13140
45	630	630	2520	2520	2520	2520	2520	2520	13797	13797	0	0	13797

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*Drivetrain shifted to high gear

TABLE 5.4-9. ELEMENT SPEED SUMMARY AT MAXIMUM STEER
FOR MOTOR THRU FINAL DRIVE IN RPM

19.5 TON GARRETT (I-10)

VEHICLE SPEED MPH	AVG. SPKT	MIN RADIUS FT	TRACK	(24 DIA) SPKT	FINAL DRIVE		TWO SPEED GEARBOX				MOTOR	
					CARRIER	(3.5 DIA) SUN	(10.5 DIA) RING	SECOND PLANETARY		FIRST PLANETARY		
								CARRIER	(3.0 DIA) SUN	(6.0 DIA) RING		CARRIER
Pivot	0	N/A	Outside Inside	27 -27	27 -27	108 -108	108 -108	324 -324	0 0	324 -324	1774 -1774	0 0
7	100	8	Outside Inside	175 26	175 26	700 104	700 104	2100 312	0 0	2100 312	11498 1708	0 0
14	200	22	Outside Inside	256 145	256 145	1024 580	1024 580	3072 1740	0 0	3072 1740	16819 9526	0 0
21	300	43	Outside Inside	343 257	343 257	1372 1028	1372 1028	1372 1028	1372 1028	1372 1028	7512 5628	0 0
28	410	77	Outside Inside	433 368	433 368	1732 1472	1732 1472	1732 1472	1732 1472	1732 1472	9483 8059	0 0
35	510	121	Outside Inside	526 475	526 475	2104 1900	2104 1900	2104 1900	2104 1900	2104 1900	11519 10402	0 0
42	600	175	Outside Inside	622 579	622 579	2488 2316	2488 2316	2488 2316	2488 2316	2488 2316	13622 12680	0 0
45	630	193	Outside Inside	651 610	651 610	2604 2440	2604 2440	2604 2440	2604 2440	2604 2440	14257 13359	0 0

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*Drivetrain shifted to high gear at 15 mph.

TABLE 5.4-10. ELEMENT SPEED SUMMARY FOR MOTOR
THRU FINAL DRIVE IN RPM

19.5 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED MPH	(24 DIA) SPROCKET	FINAL DRIVE		(10.5 (DIA) RING		CARRIER	SINGLE SPEED COMBINING GEARBOX			
		CARRIER	(3.5 DIA) SUN				(3.0 DIA) SUN	(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION	MOTOR
0	0	0	0	0	0	0	0	0	0	0
5	70	70	280	0	0	280	0	373	-1119	-1119
7	100	100	400	0	0	400	0	533	-1599	-1599
14	200	200	800	0	0	800	0	1067	-3201	-3201
15	210	210	840	0	0	840	0	1120	-3360	-3360
*15	210	210	840	0	0	840	2600	253	-759	-759
21	300	300	1200	0	0	1200	2600	732	-2196	-2196
28	400	400	1600	0	0	1600	2600	1266	-3798	-3798
35	500	500	2000	0	0	2000	2600	1800	-5400	-5400
42	600	600	2400	0	0	2400	2600	2333	-6999	-6999
45	630	630	2520	0	0	2520	2600	2493	-7480	-7480

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*Shift to electro-mechanical power combination.

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TABLE 5.4-11. ELEMENT SPEED SUMMARY AT MAXIMUM STEER FOR
MOTOR THRU FINAL DRIVE IN RPM

19.5 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED MPH	AVG SPKT	MIN RADIUS FT	TRACK	(24 DIA) SPKT	FINAL DRIVE			SINGLE SPEED COMBINING GEARBOX						
					CARRIER	(3.5 DIA)		(10.5 DIA) RING	CARRIER	(3.0 DIA)		(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION	MOTOR
						SUN	RING			SUN	RING			
Pivot	0	N/A	Outside Inside	27 -27	27 -27	108 -108	0 0	108 -108	0 0	144 -144	-432 432	-432 432		
7	100	8	Outside Inside	175 26	175 26	700 104	0 0	700 104	0 0	931 138	-2793 -414	-2793 -414		
14	200	22	Outside Inside	256 145	256 145	1024 580	0 0	1024 580	2600 2600	497 +93	-1492 -279	-1492 -279		
* 21	300	43	Outside Inside	343 257	343 257	1372 1028	0 0	1372 1028	2600 2600	960 503	-2880 -1508	-2880 -1508		
28	400	77	Outside Inside	433 368	433 368	1732 1472	0 0	1732 1432	2600 2600	1439 1093	-4317 -3279	-4317 -3279		
35	500	121	Outside Inside	526 475	526 475	2104 1900	0 0	2104 1900	2600 2600	1934 1663	-5802 -4989	-5802 -4989		
42	600	175	Outside Inside	622 579	622 579	2488 2316	0 0	2488 2316	2600 2600	2444 2216	-7334 -6647	-7334 -6647		
45	630	193	Outside Inside	651 610	651 610	2604 2440	0 0	2604 2440	2600 2600	2598 2380	-7796 -7142	-7796 -7142		

*Shift to electro-mechanical power combination after 7.14 mph.

TABLE 5.4-12. ELEMENT SPEED SUMMARY FOR MOTOR
THRU FINAL DRIVE IN RPM

40.0 TON GARRETT (I-3)

VEHICLE SPEED (24 DIA) MPH SPROCKET		TWO SPEED GEARBOX									
		SECOND PLANETARY					FIRST PLANETARY				
		(12.0 DIA) RING		(3.5 DIA) SUN		(7.0 DIA) RING	(1.75 DIA) CARRIER SUN		(7.8 DIA) RING		MOTOR
0	0	0	0	0	0	0	0	0	0	0	0
5	70	0	280	840	0	0	840	4600	0	0	4600
7	100	0	400	1200	0	0	1200	6570	0	0	6570
14	200	0	800	2400	0	0	2400	13140	0	0	13140
15	210	0	840	2520	0	0	2520	13797	0	0	13797
*15	210	0	840	840	840	840	840	4600	0	0	4600
21	300	0	1200	1200	1200	1200	1200	6570	0	0	6570
28	400	0	1600	1600	1600	1600	1600	8760	0	0	8760
35	500	0	2000	2000	2000	2000	2000	10950	0	0	10950
42	600	0	2400	2400	2400	2400	2400	13140	0	0	13140
45	630	0	2520	2520	2520	2520	2520	13797	0	0	13797

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*Drivetrain shifted to high gear

TABLE 5.4-13. ELEMENT SPEED SUMMARY AT MAXIMUM STEER FOR
MOTOR THRU FINAL DRIVE IN RPM

40.0 TON GARRETT (I-3)

VEHICLE SPEED DIA)	MPH	SPKT	FT	TRACK	SPKT	TWO SPEED GEARBOX									
						FINAL DRIVE					SECOND PLANETARY				
						(24 DIA)					(4.0 DIA) (12.0 DIA)				
						CARRIER	SUN	RING	CARRIER	SUN	RING	CARRIER	SUN	RING	MOTOR
Pivot	0	N/A		Outside	32	32	128	0	128	384	0	384	2102	0	2102
				Inside	-32	-32	-128	0	-128	-384	0	-384	-2102	0	-2102
7	100	10		Outside	176	176	704	0	704	2112	0	2112	11563	0	11563
				Inside	26	26	104	0	104	312	0	312	1708	0	1708
14	200	27		Outside	259	259	1036	0	1036	3108	0	3108	17016	0	17016
				Inside	144	144	576	0	144	1728	0	1728	9461	0	9461
*21	300	52		Outside	347	347	1388	0	1388	1388	1388	1388	7599	0	7599
				Inside	256	256	1024	0	1024	1024	1024	1024	5606	0	5606
28	400	86		Outside	439	439	1756	0	1756	1756	1756	1756	9614	0	9614
				Inside	366	366	1464	0	1464	1464	1464	1464	8015	0	8015
35	500	132		Outside	533	533	2132	0	2132	2132	2132	2132	11673	0	11673
				Inside	473	473	1892	0	1892	1892	1892	1892	10359	0	10359
42	600	190		Outside	629	629	2516	0	2516	2516	2516	2516	13775	0	13775
				Inside	579	579	2316	0	2316	2316	2316	2316	12680	0	12680
45	630	205		Outside	658	658	2632	0	2632	2604	2604	2604	14410	0	14410
				Inside	610	610	2440	0	2440	2440	2440	2440	13359	0	13359

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*Drivetrain shifted to high gear at 15 mph.

TABLE 5.4-14. ELEMENT SPEED SUMMARY FOR MOTOR THRU
FINAL DRIVE IN RPM

40.0 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED MPH	(24 DIA) SPROCKET	VEHICLE DRIVE		(10.5 (DIA) RING	CARRIER	SINGLE SPEED COMBINING GEARBOX				MOTOR
		(3.5 DIA) SUN	CARRIER			(3.0 DIA) SUN	(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION		
0	0	0	0	0	0	0	0	0	0	0
5	70	280	70	0	280	0	373	-1119	-1119	-1119
7	100	400	100	0	400	0	533	-1600	-1600	-1600
14	200	800	200	0	800	0	1066	-3199	-3199	-3199
15	210	840	210	0	840	0	1120	-3359	-3359	-3359
*15	210	840	210	0	840	3200	53	-159	-159	-159
21	300	1200	300	0	1200	3200	532	-1600	-1600	-1600
28	400	1600	400	0	1600	3200	1066	-3199	-3199	-3199
35	500	2000	500	0	2000	3200	1596	-4788	-4788	-4788
42	600	2400	600	0	2400	3200	2132	-6398	-6398	-6398
45	630	2520	630	0	2520	3200	2292	-6878	-6878	-6878

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*Shift to electro-mechanical power combination.

TABLE 5.4-15. ELEMENT SPEED SUMMARY AT MAXIMUM STEER FOR
MOTOR THRU FINAL DRIVE IN RPM

40.0 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED MPH	AVG. SPKT	MIN RADIUS FT	TRACK	(24 DIA) SPKT	FINAL DRIVE		CARRIER	(12.0 DIA)		CARRIER	SINGLE SPEED COMBINING GEARBOX			
					SUN	RING		SUN	RING		(3 0 DIA) SUN	(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION	MOTOR
Pivot	0	N/A	Outside Inside	32 -32	128 -128	0 0	32 -32	128 -128	0 0	128 -128	0 0	171 -171	-513 513	-513 513
7	100	9	Outside Inside	181 18	724 72	0 0	181 18	724 72	0 0	724 72	0 0	965 96	-2895 -279	-2895 -279
*14	200	22	Outside Inside	270 129	1080 516	0 0	270 129	1080 516	0 0	1080 516	3200 3200	373 379	-1119 -1137	-1119 -1137
21	300	43	Outside Inside	350 244	1400 976	0 0	350 244	1400 976	0 0	1400 976	3200 3200	800 235	-2400 -705	-2400 -705
28	400	77	Outside Inside	437 357	1748 1428	0 0	437 357	1748 1428	0 0	1748 1428	3200 3200	1265 838	-3795 -2514	-3795 -2514
35	500	122	Outside Inside	528 465	2112 1860	0 0	528 465	2112 1860	0 0	2112 1860	3200 3200	1750 1414	-5250 -4242	-5250 -4242
42	600	176	Outside Inside	622 569	2488 2276	0 0	622 569	2488 2276	0 0	2488 2276	3200 3200	2252 1969	-6756 -5907	-6756 -5907
45	630	193	Outside Inside	651 600	2604 2400	0 0	651 600	2604 2400	0 0	2604 2400	3200 3200	2407 2134	-7221 -6402	-7221 -6402

*Shift to electro-mechanical power combination after 7.1 mph.

5.4.8 Torque and Electric State of System Elements

This section presents the torque and electrical state of all drivetrain elements for propulsion and maximum steer under full power operation. Torques were determined for the three best transmission concepts over the same speed range and steer radius used to characterize the drivetrain element speeds. The following assumptions were used in the determining of the torque values and electrical state of electrical drivetrain power handling elements:

- o Ground coefficient of adhesion = 0.7
- o Rolling resistance = 100 lbs/ton
- o Gear mesh power loss = 1 percent of input torque
- o Power into an element has a (-) sign convention
- o Power out of an element has a (+) sign convention

It was also necessary to specify physical and performance characteristics of the 19.5 ton and 40 ton vehicles before the drivetrain element torque calculations could be made. The following characteristics were supplies by the contract statement of work.

	<u>19.5 Ton</u>	<u>40 Ton</u>
Track Length on Ground	150 in.	183 in.
Track Center to Center Difference	92.5 in.	110 in.
Diesel	VTA903-T	AD1000

Torque calculations for steer maneuvers were made by determining the maximum allowable turn force in a steer operation. To calculate the turn force at fixed turn radius, the overall system and regenerative efficiencies of each concept had to be defined. Example calculations for these turn forces and efficiencies can be found in the appendix section of this report. The overall and regenerative efficiencies were computed from the drivetrain element efficiencies. These efficiencies are shown for each concept drivetrain below:

	Overall <u>Efficiency</u>	Regenerative <u>Efficiency</u>
ACEC (I-5)	82	79
Garrett (I-9)	78	70
Unique Mobility (IV-2)	86	86

The power available at the generator gearbox was discounted for engine cooling and system parasitic power requirements. A GDLS system analysis determined that 427 HP was available to the transmission of the 19.5 ton concepts with 855 HP available for the 40 ton concepts. These calculations are also found in section 5.4.4.

5.4.8.1 19.5 Ton Torque Tables

Table 5.4-16 shows the element torque summary for the motor through final drive of the ACEC concept in the straight ahead mode.

The positive and negative values shown in the table reflect the sense of power flow in this electric drive concept. Negative values mean power out from an element while positive values mean power supplied to that element. The pinion torques are the actual output motor shaft torques estimated from the overall system efficiency and the engine available horsepower. The system efficiency will vary because the motor efficiency varies with the speed of the motor. This is a fundamental operation characteristic of the motors employed.

The development of the tables follow the approach used for the speed tables. System element torques are found by calculating from the motor shaft to the final drive sprocket. However, unlike speed, torque is not transferred through a gear set without loss, i.e., transfer of rotational power will not be 100 percent efficient in a drivetrain using gears. This is why the sun and ring gear torques in the torque tables do not add to the carrier torque.

Table 5.4-17 shows the element torque summary for motor thru final drive of the ACEC electric drive concept during maximum steer conditions.

TABLE 5.4-16. ELEMENT TORQUE SUMMARY FOR MOTOR THRU
FINAL DRIVE IN FT-LBS, 19.5 TON ACEC (1-5)

VEHICLE SPEED MPH	SPROCKET RPM	(24 DIA) SPROCKET	CARRIER	FINAL DRIVE		TWO SPEED GEARBOX			
				(3.5 DIA) SUN	(10.5 DIA) RING	PLANETARY GEAR		OFFSET GEAR	
						(3.0 DIA) SUN	(6.0 DIA) RING	(7.85 DIA) IDLER	(3.5 DIA) PINION
0	0	-12780	-12780	3260	9781	1108	2217	-1108	-499
5	70	-12780	-12780	3260	978	1108	2217	-1108	-499
7	100	-9014	-9014	2299	6898	782	1564	-782	-352
14	200	-4580	-4580	1168	3504	397	794	-397	-179
15	210	-4373	-4373	1115	3347	379	759	-379	-170
*15	210	-4347	-4347	1108	3260	1108	-739	-1108	-499
21	300	-3061	-3061	780	2342	780	-520	-780	-351
28	400	-2311	-2311	589	1768	589	-393	-589	-265
35	500	-1860	-1860	474	1423	474	-316	-474	-213
42	600	-1558	-1558	397	1192	397	-265	-397	-179
45	630	-1487	-1487	379	1138	379	-253	-379	-170

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*Drivetrain shifted to high gear.

TABLE 5.4-17. ELEMENT TORQUE SUMMARY FOR MOTOR THRU
FINAL DRIVE DURING MAXIMUM STEER IN FT-LBS

19.5 TON ACEC (I-5)

VEHICLE SPEED MPH	AVG SPKT RPM	MIN RADIUS FT	TRACK	REQ'D SPKT TORQUE	FINAL DRIVE (3.5 DIA)		CARRIER		(10.5 DIA) RING		CARRIER		TWO SPEED COMBINING GEARBOX			
													PLANETARY GEAR		OFFSET GEAR	
													(3.0 DIA) SUN	(6.0 DIA) RING	(7.85 DIA) IDLER	(3.5 DIA) PINION
Pivot	0	N/A	Inside	18654	18654	-4756	18654	18654	14270	14270	4756	4756	-1617	-3234	-1617	728
			Outside	-18654	-18654	4756	-18654	-18654	14270	14270	-4756	-4756	1617	3234	1617	-728
7	100	8	Inside	8962	8962	-2195	8962	8962	-6589	-6589	2195	2195	-717	-1434	-717	316
			Outside	-10912	-10912	2782	-10912	-10912	8347	8347	-2782	-2782	946	1892	946	-426
14	200	22	Inside	8341	8341	-2043	8341	8341	-6130	-6130	2043	2043	-667	-1335	-667	294
			Outside	-10291	-10291	2624	-10291	-10291	7872	7872	-2624	-2624	892	1784	892	-401
*21	300	43	Inside	6700	6700	-1641	6700	6700	-4924	-4924	547	547	-1641	1093	-1641	724
			Outside	-8650	-8650	2205	-8650	-8650	6617	6617	-735	-735	2205	-1471	2205	-993
28	400	77	Inside	5014	5014	-1228	5014	5014	-3685	-3685	410	410	-1228	819	-1228	542
			Outside	-6964	-6964	1775	-6964	-6964	5327	5327	-592	-592	1775	-1184	1775	-799
35	500	121	Inside	3594	3594	-880	3594	3594	-2641	-2641	294	294	-880	587	-880	388
			Outside	-5544	-5544	1413	-5544	-5544	4241	4241	-471	-471	1413	-942	1413	-636
42	600	175	Inside	2440	2440	-597	2440	2440	-1793	-1793	199	199	-597	399	-597	263
			Outside	-4391	-4391	1119	-4391	-4391	3359	3359	-373	-373	1119	-746	1119	-504
45	630	193	Inside	2042	2042	-500	2042	2042	-1500	-1500	167	167	-500	333	-500	220
			Outside	-3992	-3992	1017	-3992	-3992	3053	3053	-339	-339	1017	-679	1017	-458

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*Drivetrain shifted to high gear at 15 mph.

Torques under maximum steer were found by starting with the theoretical torque required at the drive sprocket and then calculating torque for each drivetrain element up to the motor shaft. The theoretical torque at the sprocket is fixed by the turn radius, speed, steering force, and vehicle weight and physical characteristics. This independence of theoretical sprocket torque allows each concept drivetrain to be evaluated on its merits. This evaluation is concerned with the ability of a given drivetrain to develop a torque that would meet or exceed the theoretical torque required under the given turn condition. The element torque values shown in the table are calculated as described for the straight-forward case with appropriate corrections made for efficiency.

Table 5.4-18 shows the element torque summary for motor through final drive of the Garrett drivetrain concept in the straight ahead mode.

The discussion of this table follows exactly as for the ACEC drivetrain. Table 5.4-19 shows the element torque summary for the Garrett drivetrain concept in the maximum steer mode.

The element torques for the Unique Mobility 19.5 ton concept are shown in tables 5.4-20 and 5.4-21.

5.4.8.2 40 Ton Torque Tables

This section presents the torque calculated for the 40 ton electric drive concepts in the straight ahead or maximum steer mode. The rationale and calculation methodology follow as described in the previous section. The essential difference between these two sets of calculations is the size of the engine and the developed torques due to the greater vehicle weight.

Tables 5.4-22 and 5.4-23 show the element torque summary for the Garrett drivetrain concept in the 40 ton vehicle class.

Tables 5.4-24 and 5.4-25 give the element torque values for the Unique Mobility electric drive concept in the 40 ton vehicle class.

TABLE 5.4-18. ELEMENT TORQUE SUMMARY FOR MOTOR THRU
FINAL DRIVE IN FT-LBS

19.5 TON GARRETT (1-10)

VEHICLE SPEED MPH	SPROCKET RPM	(24 DIA) SPROCKET	CARRIER	FINAL DRIVE		TWO SPEED GEARBOX			
				(3.5 DIA) SUN	(10.5 DIA) RING	PLANETARY GEAR		OFFSET GEAR	
						(3.0 DIA) SUN	(6.0 DIA) RING	CARRIER	(1.5 DIA) SUN (6.7 DIA) RING
0	0	-12246	-12246	3124	9372	1062	2125	-1062	198 885
5	70	-12246	-12246	3124	9372	1062	2125	-1062	198 885
7	100	-8514	-8514	2171	6515	738	1477	-738	137 615
14	200	-4159	-4159	1061	3183	360	721	-360	67 300
15	210	-3951	-3951	1007	3023	342	685	-342	64 285
*15	210	-4029	-4029	1028	3084	1028	-685	-1028	191 857
21	300	-2895	-2895	738	2216	738	-493	-738	137 615
28	400	-2156	-2156	550	1650	550	-367	-550	102 458
35	500	-1710	-1710	436	1308	436	-291	-436	81 363
42	600	-1413	-1413	360	1081	360	-240	-360	67 300
45	630	-1343	-1343	342	1028	342	-229	-342	64 285

*Drivetrain shifted to high gear.

TABLE 5.4-19. ELEMENT TORQUE SUMMARY AT MAXIMUM STEER CONDITIONS
IN FT-LBS FOR MOTOR THRU FINAL DRIVE

19.5 TON GARRETT (I-10)

VEHICLE SPEED MPH	AVG SPKT RPM	MIN RADIUS FT	TRACK	REQ'D SPKT TORQUE	FINAL DRIVE			TWO SPEED GEARBOX					
					CARRIER	(3.5 DIA)		CARRIER	(3.0 DIA)		CARRIER	(1.5 DIA)	
						SUN	RING		SUN	RING		SUN	RING
Pivot	0	N/A	Inside Outside	18654 -18654	-4756 4756	18654 -18654	-14270 14270	4756 -4756	1617 -1617	-3234 3234	1617 -1617	-301 301	-1345 1345
7	100	8	Inside Outside	8962 -10912	-2195 2782	8962 -10912	-6587 8347	2195 -2782	717 -946	-1434 1892	717 -946	-128 176	-573 786
14	200	22	Inside Outside	8341 -10291	2043 -2624	8341 -10291	-6130 7872	2043 -2624	667 -892	-1335 1784	667 -892	-119 166	-533 742
*21	300	43	Inside Outside	6700 -8648	-1641 2205	6700 -8648	-4924 6617	547 -735	-1641 2205	1094 -1471	1641 -2205	-293 410	-1312 1835
28	400	77	Inside Outside	5014 -6964	-1228 1775	5014 -6964	-3685 5327	410 -592	-1228 1775	819 -1184	1228 -1775	-219 330	-981 1477
35	500	121	Inside Outside	3594 -5544	-880 1413	3594 -5544	-2641 4241	294 -471	-880 1413	587 -942	880 -1413	-157 263	-703 1176
42	600	175	Inside Outside	2440 -4391	-597 1119	2440 -4391	-1793 3359	199 -373	-597 1119	399 -746	597 -1119	-107 208	-477 931
45	630	193	Inside Outside	2042 -3992	-500 1017	2042 -3992	-1500 3053	167 -339	-500 1017	333 -679	500 -1017	-89 189	-400 846

*Drivetrain shifted to high gear at 15 mph.

TABLE 5.4-20. ELEMENT TORQUE SUMMARY FOR
MOTOR THRU FINAL DRIVE IN FT-LBS

19.5 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED MPH	SPROCKET RPM	(24 DIA) SPROCKET	CARRIER	FINAL DRIVE		CARRIER	SINGLE SPEED COMBINING GEARBOX		
				(3.5 DIA) SUN	(10.5 DIA) RING		(3.0 DIA) SUN	(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION
0	0	-12804	-12804	3266	9603	-3266	833	2499	-841
5	70	-12804	-12804	3266	9603	-3266	833	2499	-841
7	100	-8959	-8959	2285	6856	-2285	583	1749	-589
14	200	-4441	-4441	1133	3399	-1133	291	864	-294
15	210	-4351	-4351	1110	3330	-1110	277	832	-280
15	210	-4845	-4845	1236	3708	-1236	315	945	-318
21	300	-3274	-3274	835	2505	-835	213	639	-215
28	400	-2402	-2402	613	1838	-613	156	469	-157
35	500	-1898	-1898	484	1453	-484	123	370	-124
42	600	-1571	-1571	400	1203	-400	102	306	-103
45	630	-1490	-1490	380	1117	-380	96	291	-97

*Shift to electro-mechanical power combination

TABLE 5.4-21. ELEMENT TORQUE SUMMARY AT MAXIMUM STEER CONDITION FOR
MOTOR THRU FINAL DRIVE IN FT-LBS

19.5 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED	AVG SPROCKET RPM	MIN RADIUS FT	TRACK	REQ'D SPROCKET TORQUE	FINAL DRIVE		SINGLE SPEED COMBINING GEARBOX					
					CARRIER	(3.5 DIA) SUN	(10.5 DIA) RING	CARRIER	(3.0 DIA) SUN	(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION	
MPH												
Pivot	0	0	Inside Outside	18654 -18654	18654 -18654	-4756 4756	-14270 14270	4756 -4756	-1212 1212	-3638 3638	-1225 1225	
7	100	7	Inside Outside	9006 -10956	9006 -10956	-2206 2793	-6619 8381	2206 -2793	-540 712	-1621 2137	-535 719	
14	200	22	Inside Outside	8341 -10291	8341 -10291	-2043 2624	-6130 7872	2043 -2624	-500 669	-1502 2007	-495 675	
21	300	43	Inside Outside	6700 -8650	6700 -8650	-1641 2205	-4924 6617	1641 -2205	-402 562	-1206 1687	-398 568	
28	400	77	Inside Outside	5014 -6964	5014 -6964	-1228 1776	-3685 5328	1228 -1776	-300 452	-902 1358	-297 461	
35	500	121	Inside Outside	3594 -5544	3594 -5544	-880 1413	-2641 4241	880 -1413	-215 360	-647 1081	-213 364	
42	600	175	Inside Outside	2440 -4391	2440 -4391	597 1119	1793 3359	597 -1119	-146 285	-439 856	-145 288	
45	630	193	Inside Outside	2042 -3992	2042 -3992	-500 1017	-1500 3053	500 -1017	-122 259	-367 778	-121 262	

TABLE 5.4-22. ELEMENT TORQUE SUMMARY FOR MOTOR
THRU FINAL DRIVE IN FT-LBS

40.0 TON GARRETT (1-3)

SPEED MPH	SPROCKET RPM	(24 DIA) SPROCKET	FINAL DRIVE			SECOND PLANETARY			FIRST PLANETARY		
			CARRIER	(4.0 DIA) SUN	(12.0 DIA) RING	CARRIER	(3.5 DIA) SUN	(7.0 DIA) RING	CARRIER	(1.75 DIA) SUN	(7.8 DIA) RING
0	0	-25480	-25480	6500	19500	-6500	2211	4422	-2211	412	1844
5	70	-25480	-25480	6500	19500	-6500	2211	4422	-2211	412	1844
7	100	-17750	-17750	4528	13584	-4528	1540	3080	-1540	287	1284
14	200	-8655	-8655	2208	6624	-2208	751	1502	-751	140	627
15	210	-8228	-8228	2099	6297	-2099	714	1428	-714	133	595
*15	210	-8667	-8667	2211	6633	-737	2211	-1474	-2211	412	1844
21	300	-6037	-6037	1540	4620	-513	1540	-1027	-1540	287	1284
28	400	-4481	-4481	1143	3429	-381	1143	-762	-1143	213	953
35	500	-3575	-3575	912	2736	-304	912	-608	-912	170	761
42	600	-2944	-2944	751	2253	-250	751	-501	-751	140	627
45	630	-2799	-2799	714	2142	-238	714	-476	-714	133	595

*Drivetrain shifted to high gear.

TABLE 5.4-23. ELEMENT TORQUE SUMMARY AT MAXIMUM STEER CONDITIONS
IN FT-LBS FOR MOTOR THRU FINAL DRIVE

40.0 TON GARRETT (I-3)

VEHICLE SPEED MPH	AVG SPKT RPM	MIN RADIUS FT	TRACK	REQ'D SPKT TORQUE	TWO SPEED GEARBOX									
					FINAL DRIVE		SECOND PLANETARY				FIRST PLANETARY			
					(3.5 DIA) SUN	(10.5 DIA) RING	CARRIER	(3.0 DIA) SUN	(6.0 DIA) RING	CARRIER	(1.5 DIA) SUN	(6.7 DIA) RING		
Pivot	0	N/A	Outside	-37284	9511	28533	-9511	3235	6470	-3235	603	2698		
			Inside	37284	-9511	-28533	9511	-3235	-6470	3235	-603	-2698		
7	100	10	Outside	-22073	5631	16893	-5631	1915	3830	-1915	357	1598		
			Inside	18073	-4428	-13284	4428	-1446	-2892	1446	-259	-1159		
14	200	27	Outside	-20103	5128	15384	-5128	1744	3488	-1744	325	1454		
			Inside	16103	-3945	-11835	3945	-1289	-2578	1289	-231	-1034		
*21	300	52	Outside	-17102	4363	13089	-1454	4363	-2909	-4363	813	3638		
			Inside	13102	-3210	-9630	1070	-3210	2140	3210	-575	-2573		
28	400	86	Outside	-14006	3573	10719	-1191	3573	-2382	-3573	666	2980		
			Inside	10006	-2451	-7353	817	-2451	1634	2451	-439	-1965		
35	500	132	Outside	-11099	2831	8493	-944	2831	-1887	-2831	528	2363		
			Inside	7099	-1739	-5217	580	-1739	1160	1739	-311	-1392		
42	600	190	Outside	-8754	2233	6699	-744	2233	-1489	-2233	416	1862		
			Inside	4754	-1165	-3495	388	-1165	777	1163	-208	-931		
45	630	205	Outside	-8191	2090	6270	-697	2090	-1393	2090	390	1745		
			Inside	4191	-1027	-3081	342	-1027	685	1027	-184	-823		

*Drivetrain shifted to high gear at 15 mph.

TABLE 5.4-24. ELEMENT TORQUE SUMMARY FOR MOTOR
THRU FINAL DRIVE IN FT-LB

40.0 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED MPH	SPROCKET RPM	(24 DIA) SPROCKET	CARRIER	FINAL DRIVE (4.0 DIA)		CARRIER	(12.0 DIA)		SINGLE SPEED COMBINING GEARBOX		
				SUN	RING		SUN	RING	(3.0 DIA) SUN	(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION
0	0	-26354	-26354	6723	20169	-6723	1715	5144	1715	5144	-1732
5	70	-26354	-26354	6723	20169	-6723	1715	5144	1715	5144	-1732
7	100	-18424	-18424	4700	14100	-4700	1199	3597	1199	3597	-1211
14	200	-9220	-9220	2352	7056	-2352	600	1800	600	1800	-606
15	210	-8773	-8773	2238	6714	-2238	571	1714	571	1714	677
*15	210	-9910	-9910	2528	7584	-2528	645	1936	645	1936	-652
21	300	-6684	-6684	1705	5115	-1705	435	1304	435	1304	-439
28	400	-4916	-4916	1254	3762	-1254	320	959	320	959	-323
35	500	-3873	-3873	988	2964	-988	252	757	252	757	-255
42	600	-3210	-3210	819	2457	-819	209	627	209	627	-211
45	630	-3042	-3042	776	2328	-776	198	594	198	594	-200

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*Shift to electro-mechanical power combination

TABLE 5.4-25. ELEMENT TORQUE SUMMARY AT MAXIMUM STEER CONDITION
IN FT-LB (MOTOR THRU FINAL DRIVE)

40.0 TON UNIQUE MOBILITY (IV-2)

VEHICLE SPEED MPH	AVG SPROCKET RPM	MIN RADIUS FT	TRACK	REQ'D SPROCKET TORQUE	FINAL DRIVE		SINGLE SPEED COMBINING GEARBOX				
					CARRIER	(4.0 DIA) SUN	(12.0 DIA) RING	CARRIER	(3.0 DIA) SUN	(9.0 ID, 10.5 OD) RING	(3.5 DIA) PINION
Pivot	0	N/A	Outside Inside	-37284 37284	-37284 37284	9511 -9511	28533 -28533	-9511 9511	2426 -2426	7278 -7278	-2450 2450
7	100	9	Outside Inside	-22261 18261	-22261 18261	5679 -4474	17037 -13422	-5679 4474	1449 -1096	4347 -3288	-1464 1085
*14	200	22	Outside Inside	-20760 16760	-20760 16760	5296 -4106	15888 -12318	-5296 4106	1351 -1006	4053 -3018	-1365 996
21	300	43	Outside Inside	-18134 14134	-18134 14134	4626 3463	13878 -10389	-4626 3463	1180 -848	3540 -2544	-1192 840
28	400	77	Outside Inside	-14757 10757	-14757 10757	3765 -2635	11295 -7905	-3765 2635	960 -646	2880 -1938	-970 640
35	500	122	Outside Inside	-12506 8506	-12506 8506	3190 -2084	9570 -6252	-3190 2084	814 -511	2442 -1533	-822 506
42	600	176	Outside Inside	-9129 5129	-9129 5129	2329 -1257	6987 -3771	-2329 1257	594 -308	1782 -924	-600 305
45	630	293	Outside Inside	-8378 4378	-8378 4378	2137 -1073	6411 -3219	-2137 1073	545 -263	1635 -789	-551 260

*Drivetrain shifted to electro-mechanical power combination after 7.1 mph.

The electric state of the electric machinery and power electronics for the best three concepts was determined at maximum input power over the vehicle speed range for the propulsion and steer modes. Electrical state parameters for the 19.5 ton concepts are given in tables 5.4-26 through 5.4-31 and for 40.0 ton concepts are given in tables 5.4-32 through 5.4-35. These tables present the vehicle speed in terms of drive sprocket RPM similar to the previous torque tables and generally cover the speed range in 100 RPM increments. The tables include the current, voltage, and firing angle values for appropriate electric drive components. Also the torque and speed of each traction motor are presented. Finally system efficiency is tabulated for each concept, which includes on the electrical losses in the system.

5.4.9 Cooling System Analysis

The vehicle cooling system must provide adequate cooling for continuous operation at 0.7 tractive effort and 120°F ambient air temperature as indicated by the contract requirements. The cooling system of an electric drive vehicle should properly cool the electric drive system in addition to cooling the engine. The vehicle cooling system must therefore be sized to handle the heat rejection of engine and of the electric transmission.

The cooling system designs presented for the 19.5 and 40.0 ton vehicle concepts are based on engine heat rejection rates of 28 BTU/HP-MIN for the VTA-903T engine and 27 BTU/HP-MIN for the Ad1000 engine.

The heat rejection rate of the electric transmission is based on the efficiencies of the components of the system. Since the efficiency of most components varies with vehicle speed, transmission, heat rejection was computed at three operating points: 0.70 tractive effort (5 mph), shift speed (15 mph), and maximum speed (45 mph). This was done to determine the operating point of maximum heat rejection. Once determined the maximum transmission heat rejection and the engine heat rejection at full load were used as the basis for sizing of the vehicle cooling system.

The cooling system concepts presented in the following subsections are regarded as conservative designs and their optimization will result in weight and volume reduction.

TABLE 5.4-26. ELECTRICAL STATE PARAMETERS FOR PROPULSION MODE

19.5 TON ACEC CONCEPT I-5

SPROCKET SPEED (RPM)	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	RATED FIELD EXCITATION	DC CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	DRIVE TRAIN EFFICIENCY
70	1884	499	.9366	366	778	.9077	415	.862
100	2692	352	.6605	366	784	.9132	418	.863
200	5383	179	.3360	366	797	.9258	424	.865
210	5652	170	.3191	366	794	.9237	423	.864
210	1884	499	.9366	366	778	.9077	415	.862
300	2692	351	.6587	366	782	.9112	417	.863
400	3589	265	.4974	366	787	.9162	419	.863
500	4486	213	.3996	366	790	.9192	421	.864
600	5383	179	.3360	366	797	.9258	424	.865
630	5652	170	.3191	366	794	.9237	423	.864

TABLE 5.4-27. ELECTRICAL STATE PARAMETERS FOR STEER MODE

19.5 TON ACEC CONCEPT 1-5

AVERAGE SPROCKET SPEED (RPM)	RADIUS OF TURN (FT)	MOTOR LOCATION	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	RATED FIELD EXCITATION (PU)	DC CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	STEER EFFICIENCY
100	8	Outside Inside	4710 700	426 -316	.7995 -.5930	366	742	.8711	397	.869
200	22	Outside Inside	6890 3902	401 -294	.6271 -.4599	439	571	.7370	389	.866
300	43	Outside Inside	3077 2306	993 -724	1.1647 -.8491	586	385	.6221	405	.804
400	77	Outside Inside	3885 3302	799 -542	1.0710 -.7265	513	414	.6152	360	.844
500	121	Outside Inside	4719 4262	636 -388	.9947 -.6067	439	485	.6514	338	.875
600	175	Outside Inside	5580 5195	504 -263	.9460 -.4935	366	610	.7408	333	.903
630	193	Outside Inside	5840 5472	458 -220	.8594 -.4129	366	620	.7499	337	.899

TABLE 5.4-28. ELECTRICAL STATE PARAMETERS FOR PROPULSION MODE

19.5 TON GARRETT CONCEPT I-10

SPROCKET SPEED (RPM)	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	DRIVE TRAIN EFFICIENCY
70	4600	198	.7734	367	781	.9103	417	.831
100	6570	137	.5124	367	779	.9084	416	.823
200	13140	67	.2168	367	794	.9234	423	.790
210	13797	64	.2046	367	800	.9295	426	.788
210	4600	191	.7431	367	756	.8854	405	.826
300	6570	137	.5124	367	779	.9084	416	.823
400	8760	102	.3636	367	783	.9118	418	.814
500	10950	81	.2750	367	787	.9167	420	.802
600	13140	67	.2168	367	794	.9234	423	.791
630	13797	64	.2046	367	800	.9295	426	.788

TABLE 5.4-29. ELECTRICAL STATE PARAMETERS FOR STEER MODE

19.5 TON GARRETT CONCEPT I-10

AVERAGE SPROCKET SPEED (RPM)	RADIUS OF TURN (FT)	MOTOR LOCATION	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	STEER EFFICIENCY
100	8	Outside	11498	176	.6850	367	785	.9142	419	.836
		Inside	1708	-128	-.6338					
200	22	Outside	16819	166	.6468	367	757	.8865	405	.856
		Inside	9526	-119	-.5880					
300	43	Outside	7512	410	.8665	642	439	.6647	472	.746
		Inside	5628	-293	-.8653					
400	77	Outside	9483	330	.8648	532	477	.6649	406	.803
		Inside	8059	-219	-.7674					
500	121	Outside	11519	263	.8524	440	560	.7157	376	.839
		Inside	10402	-157	-.6565					
600	175	Outside	13622	208	.8247	367	684	.8142	369	.859
		Inside	12680	-107	-.5334					
630	193	Outside	14257	189	.7434	367	700	.8294	377	.850
		Inside	13359	-89	-.4550					

TABLE 5.4-30. ELECTRICAL STATE PARAMETERS FOR PROPULSION MODE

19.5 TON UNIQUE MOBILITY CONCEPT I-10

SPROCKET SPEED (RPM)	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	DRIVE TRAIN EFFICIENCY
70	1119	841	.7992	410	709	.7988	423	.847
100	1599	589	.5464	410	713	.8031	425	.844
200	3201	294	.5166	410	695	.7829	415	.863
210	3360	280	.4908	410	696	.7839	416	.861
210	759	318	.7818	164	477	.5035	105	.876
300	2196	215	.4124	205	700	.7882	202	.890
400	3798	157	.4737	246	738	.8309	257	.885
500	5400	124	.8357	267	771	.8679	291	.878
600	6999	103	.6496	287	789	.8881	321	.856
630	7480	97	.5707	308	749	.8435	328	.840

TABLE 5.4-31. ELECTRICAL STATE PARAMETERS FOR STEER MODE

19.5 TON UNIQUE MOBILITY CONCEPT IV-2

AVERAGE SPROCKET SPEED (RPM)	RADIUS OF TURN (FT)	MOTOR LOCATION	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	STEER EFFICIENCY
100	8	Outside	2793	719	.8400	615	472	.7292	460	.726
		Inside	414	-535	-.4291					
200	22	Outside	1492	675	.6325	410	357	.5373	229	.750
		Inside	279	-495	-.5446					
300	43	Outside	2880	568	.8388	492	316	.5164	255	.843
		Inside	1508	-398	-.3890					
400	77	Outside	4317	461	.8250	410	401	.5872	254	.863
		Inside	3279	-297	-.5685					
500	121	Outside	5802	364	-.8530	738	263	.5314	360	.715
		Inside	4989	-213	-.2644					
600	175	Outside	7334	288	.8474	595	341	.5752	338	.771
		Inside	6647	-145	-.4464					
630	193	Outside	7796	262	.8648	533	385	.6063	329	.788
		Inside	7142	-121	-.4121					

TABLE 5.4-32. ELECTRICAL STATE PARAMETERS FOR PROPULSION MODE

40.0 TON GARRETT CONCEPT I-3

SPROCKET SPEED (RPM)	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	DRIVE TRAIN EFFICIENCY
70	4600	412	.7993	733	813	.9407	864	.835
100	6570	287	.5346	733	815	.9432	867	.828
200	13140	140	.2272	733	827	.9555	879	.797
210	13797	133	.2130	733	830	.9579	881	.793
210	4600	412	.7993	733	813	.9407	864	.835
300	6570	287	.5346	733	815	.9432	867	.828
400	8760	213	.3788	733	816	.9439	867	.819
500	10950	170	.2893	733	825	.9526	876	.809
600	13140	140	.2272	733	827	.9555	879	.797
630	13797	133	.2130	733	830	.9579	881	.793

TABLE 5.4-33. ELECTRICAL STATE PARAMETERS FOR STEER MODE

40.0 TON GARRETT CONCEPT I-3

AVERAGE SPROCKET SPEED (RPM)	RADIUS OF TURN (FT)	MOTOR LOCATION	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	STEER EFFICIENCY
100	10	Outside Inside	11563 1708	357 -259	.6883 -.6335	733	792	.9199	844	.847
200	27	Outside Inside	17016 9461	325 -231	.6250 -.5669	733	755	.8832	807	.861
300	52	Outside Inside	7599 5606	813 -575	.8488 -.8427	1284	435	.6598	935	.760
400	86	Outside Inside	9614 8015	666 -439	.8645 -.7607	1064	486	.6726	823	.816
500	132	Outside Inside	11673 10359	528 -311	.8468 -.6442	880	574	.7287	768	.849
600	190	Outside Inside	13775 12680	416 -208	.8161 -.5148	733	704	.8328	757	.866
630	205	Outside Inside	14410 13359	390 -184	.7612 -.4631	733	721	.8497	774	.861

TABLE 5.4-34. ELECTRICAL STATE PARAMETERS FOR PROPULSION MODE

40.0 TON UNIQUE MOBILITY CONCEPT IV-2

SPROCKET SPEED (RPM)	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	DRIVE TRAIN EFFICIENCY
70	1119	1732	.8488	820	707	.9310	843	.875
100	1599	1211	.5879	820	711	.9350	847	.870
200	3201	606	.5528	820	715	.9395	851	.867
210	3360	577	.5265	820	716	.9413	853	.865
210	759	652	.8132	328	450	.5668	211	.893
300	2196	439	.4377	410	709	.8714	409	.889
400	3798	323	.5067	492	769	.9507	533	.875
500	5400	255	.8189	574	767	.9613	625	.839
600	6999	211	.6467	615	777	.9788	680	.827
630	7480	200	.5789	656	749	.9539	703	.810

TABLE 5.4-35. ELECTRICAL STATE PARAMETERS FOR STEER MODE

40.0 TON UNIQUE MOBILITY CONCEPT IV-2

AVERAGE SPROCKET SPEED (RPM)	RADIUS OF TURN (FT)	MOTOR LOCATION	MOTOR SPEED (RPM)	MOTOR TORQUE (FT-LB)	MOTOR COSINE OF FIRING ANGLE	DC LINK CURRENT (AMPS)	RECTIFIER DC OUTPUT VOLTAGE	RECTIFIER COSINE OF FIRING ANGLE	GENERATOR INPUT POWER (HP)	STEER EFFICIENCY
100	9	Outside Inside	2895 279	1464 -1085	.8510 -.3881	1272	480	.7436	966	.788
200	22	Outside Inside	1119 1137	1365 -996	.6644 -.5222	820	105	.2527	181	.734
300	43	Outside Inside	2400 705	1192 -840	.5798 -.4446	820	433	.6228	542	.831
400	77	Outside Inside	3795 2514	970 -640	.8453 -.5669	861	385	.5738	515	.853
500	122	Outside Inside	5250 4242	822 -506	.8626 -.2491	1682	236	.5306	784	.689
600	176	Outside Inside	6756 5907	600 -305	.8180 -.4092	1313	309	.5564	700	.740
630	193	Outside Inside	7221 6402	551 -260	.8049 -.3682	1231	339	.5778	697	.746

The cooling system fan power used for the analysis is 60 HP for the 19.5 ton vehicle and 120 HP for the 40.0 ton vehicle. The fan horsepower is dependent on the air flow rate required for adequate cooling and the pressure drop in the cooling system. The pressure drop includes the air flow resistance of the inlet and exhaust grilles, of the heat exchanger core, and of the engine compartment. Fan efficiency was assumed to be 50 percent.

5.4.9.1 Cooling System for Garrett Concepts

The cooling systems for the 19.5 and 40.0 ton Garrett transmission concepts (I-10 and I-3) were sized based on the maximum heat rejection which occurs in low gear at 15 miles per hour. Table 5.4-36 gives the maximum heat rejection of 4565 BTU/MIN for the 19.5 ton concept I-10 and 8737 BTU/MIN for the 40.0 concept I-3.

The power conditioning units (PCU) are the most temperature sensitive units in the drivetrain because maximum inlet oil temperature is limited to 200°F. Therefore, the PCUs need a separate oil to air heat exchanger. The electrical drivetrain is cooled using an oil to water shell and tube heat exchanger connected to the main heat exchanger, which is a water to air radiator. Figure 5.4-24 give the vehicle cooling system schematic. These systems use three heat exchangers as follows:

- o Oil to air cooler to cool the PCUs
- o Oil to water cooler to cool the motors, gear boxes, and generator
- o Water to air cooler to cool engine and drivetrain cooler

A summary of the heat exchanger characteristics is shown in Table 5.4-37. The hydraulic fluid is pumped from the reservoir into the tube and shell heat exchanger, and from there into a distribution manifold where the flow is branched off into the motors and the generator and back to the reservoir. See figure 5.4-25 for cooling flow diagram. Tables 5.4-38 and 5.4-39 present weight and volume estimates for the 19.5 and 40.0 ton cooling systems.

TABLE 5.4-36. TRANSMISSION EFFICIENCY AND HEAT
REJECTION FOR GARRETT CONCEPTS

	0.7 TE	SHIFT	MAX.
Vehicle Speed (mph)	5	15	45
Gear	Low	Low/High	High
Motor rpm	4600	13800/4600	13800
Generator Eff.	93.5	93.5/93.5	93.5
Transfer Case Eff.	98	98/98	98
PCU Eff.	96	94.5/96	94.5
Motor Eff.			
19.5 Ton (180 Kw)	93	90/93	90
40 Ton (360 Kw)	94	91/94	91
2 Speed Gear Box Eff.	96	96/98	98
System Eff. (19.5 Ton)	78.5	74.8/80.2	76.4
(40 Ton)	79.4	75.6/81.0	77.2
Heat Rejection Rate (BTU/min)			
(19.5 Ton)	3894	4565/3592	7275
(40 Ton)	7395	8737/6803	8170

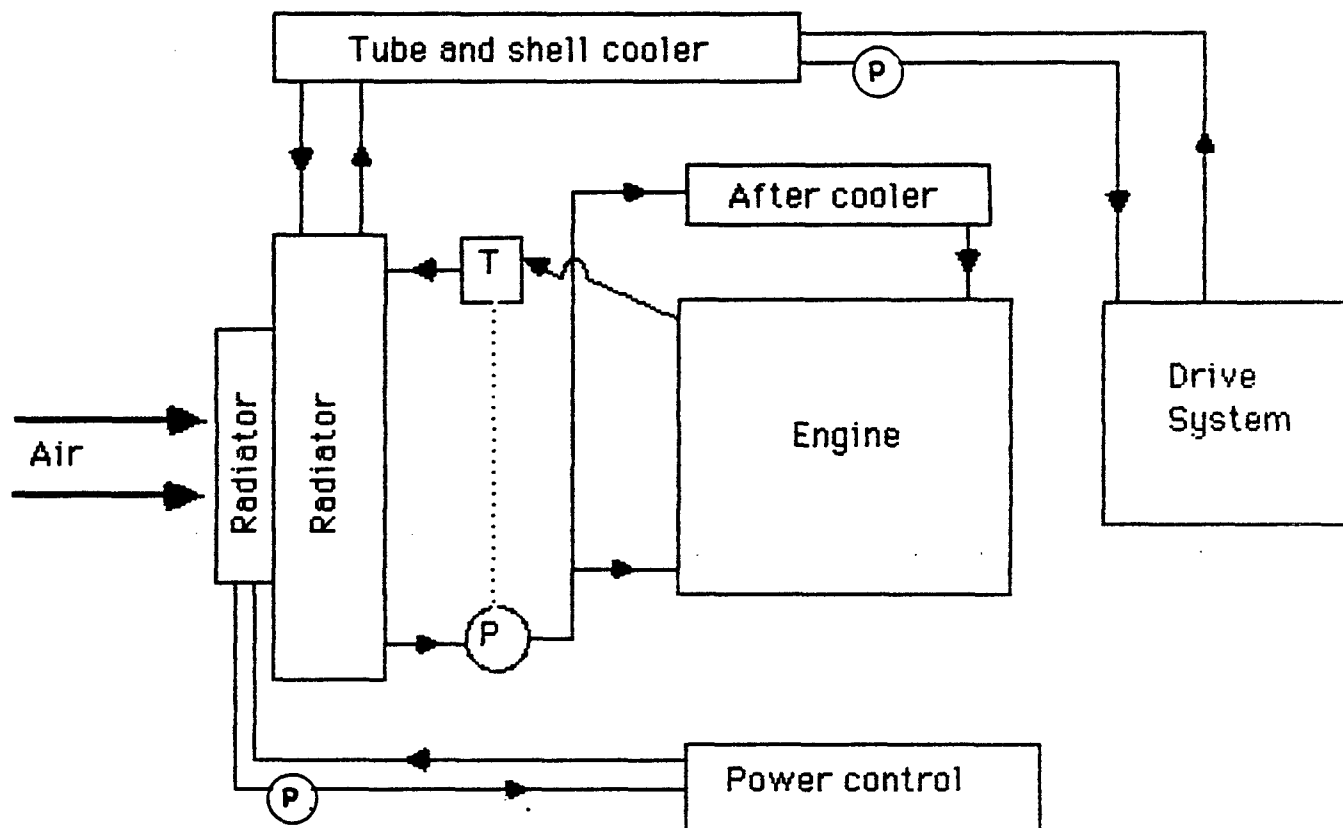


Figure 5.4-24. Cooling System for Garrett Concepts

TABLE 5.4-37. HEAT EXCHANGER CHARACTERISTICS FOR
GARRETT CONCEPTS

		19.5 TON	40 TON
PCU's COOLER			
TOIL OUT	(°F)	200	200
TOIL IN	(°F)	222	222
TAIR IN	(°F)	125	125
TAIR OUT	(°F)	133	133
AIR FLOW RATE	(FPM)	2000	2000
OIL FLOW RATE	(GPM)	12	24
HEAT REJECTION	(BTU/MIN)	913	1825
SIZE	(INCHES)	24x24x1.5	32x20x1.5
TUBE AND SHELL COOLER			
TOIL OUT	(°F)	250	250
TOIL IN	(°F)	306	305
TWATER IN	(°F)	210	200
TWATER OUT	(°F)	214	206
OIL FLOW RATE	(GPM)	36	72
WATER FLOW RATE	(GPM)	120	160
HEAT REJECTION	(BTU/MIN)	3650	7000
SIZE	(INCHES)	33x7.50D	36.25x11.0D
SYSTEM COOLER			
TWATER IN	(°F)	230	230
TWATER OUT	(°F)	210	200
TAIR IN	(°F)	133	133
TAIR OUT	(°F)	193	182.5
WATER FLOW RATE	(GPM)	120	160
AIR VELOCITY	(FPM)	2000	2000
HEAT REJECTION	(BTU/MIN)	17650	34000
SIZE	(INCHES)	36x36x7.5	53x53x7.5

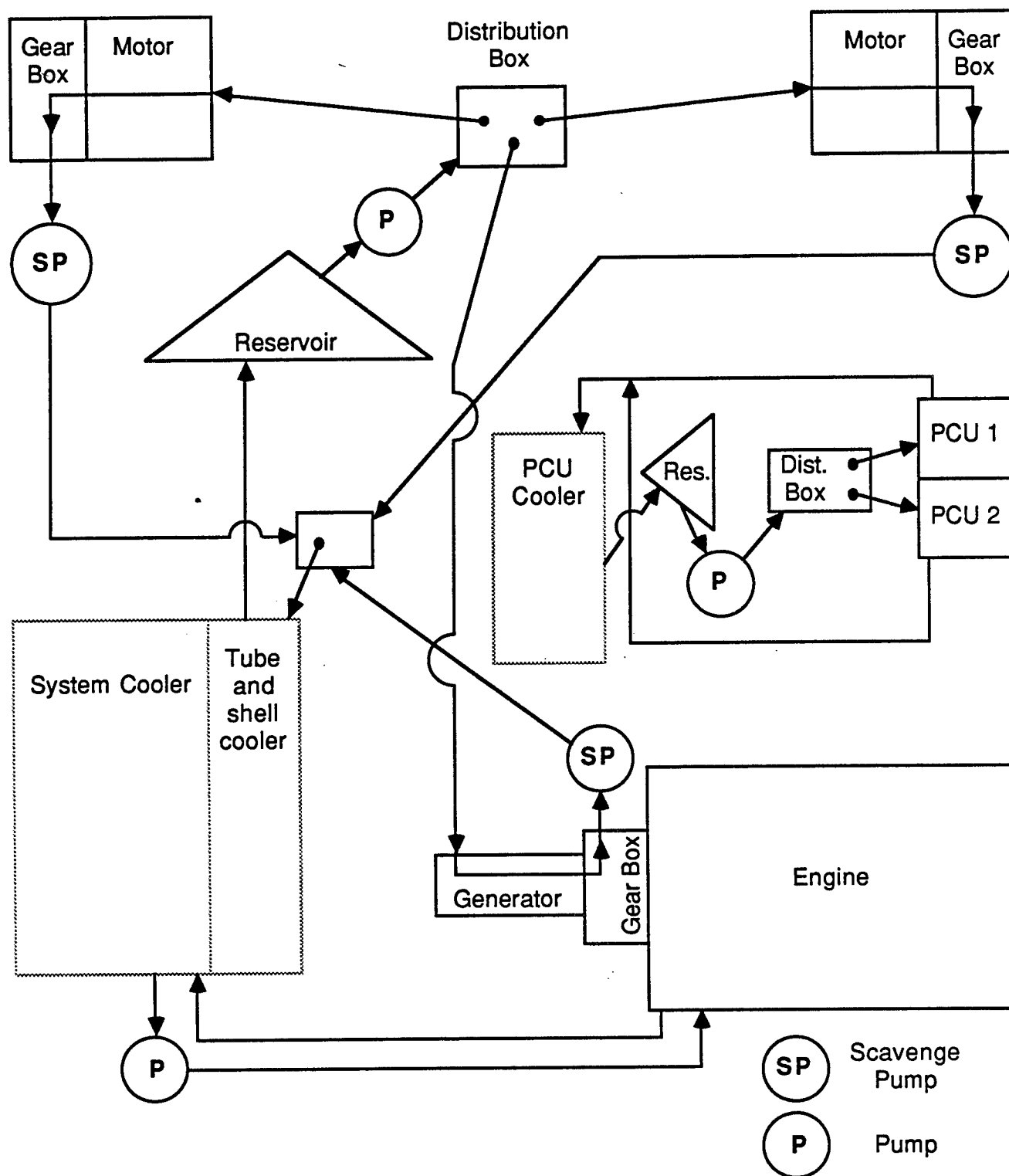


Figure 5.4-25. Cooling System Flow Diagram for Garrett Concepts

TABLE 5.4-38. 19.5 TON GARRETT CONCEPT I-10
COOLING SYSTEM WEIGHT AND VOLUME ESTIMATES

<u>DESCRIPTION</u>	<u>QUANTITY</u>	<u>UNIT</u>	<u>SYSTEM</u>	<u>UNIT</u>	<u>SYSTEM</u>
		<u>VOLUME</u>	<u>VALUE</u>	<u>WEIGHT</u>	<u>WEIGHT</u>
		<u>IN³</u>	<u>IN³</u>	<u>lb</u>	<u>lb</u>
Scavenge Pump	3	6.5	19.5	5.0	15.0
Scavenge Pump Motor	3	161.0	483.0	18.0	54.0
Manifold	1	67.5	67.5	7.1	7.1
Check Valve	3	22.0	66.0	5.0	15.0
Pressure Valve	2	22.5	45.0	1.5	3.0
Filters	2	305.3	610.3	13.0	26.0
Dump and By Pass	3	inline	-	-	-
Valves					
Gear Pump	2		212.0		40.0
Reservoir	2	1210.0	1210.0	10.0	10.0
Fans and Drives	2		610.0		160.0
PCU Cooler	1	864.0	864.0	17.0	17.0
System Cooler	1	9720.0	9720.0	254.0	254.0
Tube and Shell	1	1458.0	1458.0	70.0	70.0
Cooler					
Cool Medium	9 gal	-	-	63.0	63.0
TOTAL			15365.3		734.1

TABLE 5.4-39. 40.0 TON GARRETT CONCEPT I-3
COOLING SYSTEM WEIGHT AND VOLUME ESTIMATES

<u>DESCRIPTION</u>	<u>QUANTITY</u>	UNIT	SYSTEM	UNIT	SYSTEM
		VOLUME	VALUE	WEIGHT	WEIGHT
		<u>IN³</u>	<u>IN³</u>	<u>lb</u>	<u>lb</u>
Scavenge Pump	3	10.3	30.9	8.0	24.0
Scavenge Pump Motor	3	196.0	588.0	22.0	66.0
Manifold	1	67.5	67.5	7.1	7.1
Check Valve	3	22.0	66.0	5.0	15.0
Pressure Valve	2	22.5	45.0	1.5	3.0
Filters	2	305.3	610.6	13.0	26.0
Dump and By Pass Valves	3	In Line	In Line	-	-
Gear Pump	2		264.0		49.0
Reservoir	2	1728.0	1728.0	22.0	22.0
Fans and Drives	2		1220.0		320.0
PCU Cooler	1	1440.0	1440.0	31.0	31.0
System Cooler	1	21068.0	21068.0	551.0	551.0
Tube and Shell Cooler	1	3445.0	3445.0	90.0	90.0
Cool Medium	14 gal	-	-	-	98.3
TOTAL			30573.0		1302.4

TABLE 5.4-40. TRANSMISSION EFFICIENCY AND HEAT REJECTION
FOR ACEC CONCEPT I-5 (19.5 TON)

	<u>BASE</u>	<u>SHIFT</u>	<u>MAX.</u>
Vehicle Speed (mph)	5	15	45
Motor rpm	1886	5660/18860	5660
Gear	Low	Low/High	High
Generator Eff.	93.5	93.5/93.5	93.5
Transfer Case Eff.	98	98/98	98
Rectifier Eff.	98	98/98	98
Motor Eff. (Air Cooled)	92.5	95/92.5	95
2 Speed Gear Box Eff.	96	96/98	98
System Eff.	79.7	81.9/81.4	83.6
Heat Rejection Rate (BTU/min)	3677	3278.5/3369	2971

5.4.9.2 Cooling System for ACEC Concept

ACEC concept I-5 for the 19.5 ton vehicle utilizes DC motors and a Garrett pm generator whose output is rectified to DC. The motors in this concept are air cooled while the generator, transfer case, rectifier, and two speed gear box are oil cooled. The transmission oil cooling system size is based on a maximum heat rejection of 3677 BTU/MIN shown in table 5.4-40. In this concept the rectifiers are the most temperature sensitive units, therefore, they are cooled first. The powerpack cooling system uses an oil to air cooler for the drivetrain and a water to air cooler for the engine. (Figure 5.4-26). A summary of the heat exchanger analysis is shown in table 5.4-40. The hydraulic fluid is pumped from the reservoir into the drivetrain cooler and then into a distribution manifold where the flow is branched off as shown in figure 5.4-27. See table 5.4-42 for component size, weight, and volume estimates.

5.4.9.3 Cooling System - For Unique Mobility Concepts

Concept IV-2 for the 19.5 ton vehicle and concept IV-2 for the 40 ton vehicle both utilize 192 horsepower air cooled Unique Mobility motors.

These dual path concepts combine both mechanical and electrical drives. The efficiency of the mechanical part is a constant 92.0% and the efficiency of the electrical part is 82.7%. Over the range of the vehicle speed, the contribution of the mechanical and electrical paths change for full load operation as shown in table 5.4-43. The total system efficiency ranges from 82.7% to 89.8% (see table 5.4-44). The powerpack cooling system uses an oil to air cooler for the drivetrain and a water to air cooler for the engine cooling (figure 5.4-28). A summary of the heat exchanger analysis is shown in table 5.4-45.

The hydraulic fluid is pumped from the electrical cooler into a distribution manifold where the flow branches off as shown in figure 5.4-29. Tables 5.4-46 and 5.4-47 present weight and volume estimates for the 19.5 and 40.0 ton vehicle powerpack cooling systems. The transmission cooling systems for the 19.5 and 40.0 ton vehicles are based on maximum heat rejection rates of 3134 BTU/Min and 6268 BTU/Min, respectively.

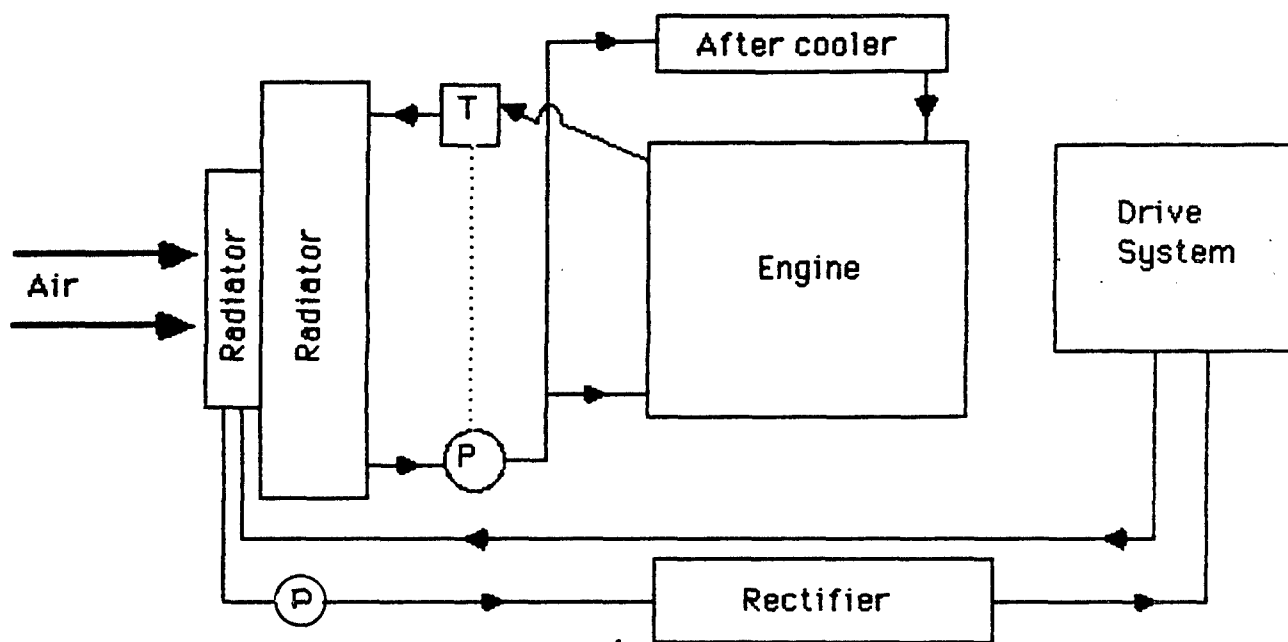


Figure 5.4-26. Cooling System for ACEC Concept

TABLE 5.4-41. HEAT EXCHANGER CHARACTERISTICS FOR
ACEC CONCEPT I-5

			19.5 TON
ELECTRICAL COOLER			
TOIL OUT	(°F)	200	
TOIL IN	(°F)	219	
TAIR IN	(°F)	125	
TAIR OUT	(°F)	133	
AIR VELOCITY	(FPM)	2000	
OIL FLOW RATE	(GPM)	36	
HEAT REJECTION	(BTU/MIN)	2466	
SIZE	(INCHES)	40x40x1.5	
MOTOR COOLING			
AIR FLOW	(ft ³ /min)	852	
REQUIRED PER MOTOR TAIR	(°F)	44°F	
HEAT REJECTION RATE	(BTU/MIN)	610	
PER MOTOR			
SYSTEM COOLER			
TWATER IN	(°F)	23	
TWATER OUT	(°F)	214	
TAIR IN	(°F)	133	
TAIR OUT	(°F)	193	
WATER FLOW RATE	(GPM)	120	
AIR VELOCITY	(FPM)	2000	
HEAT REJECTION	(BTU/MIN)	14000	
SIZE	(INCHES)	32x32x7.5	

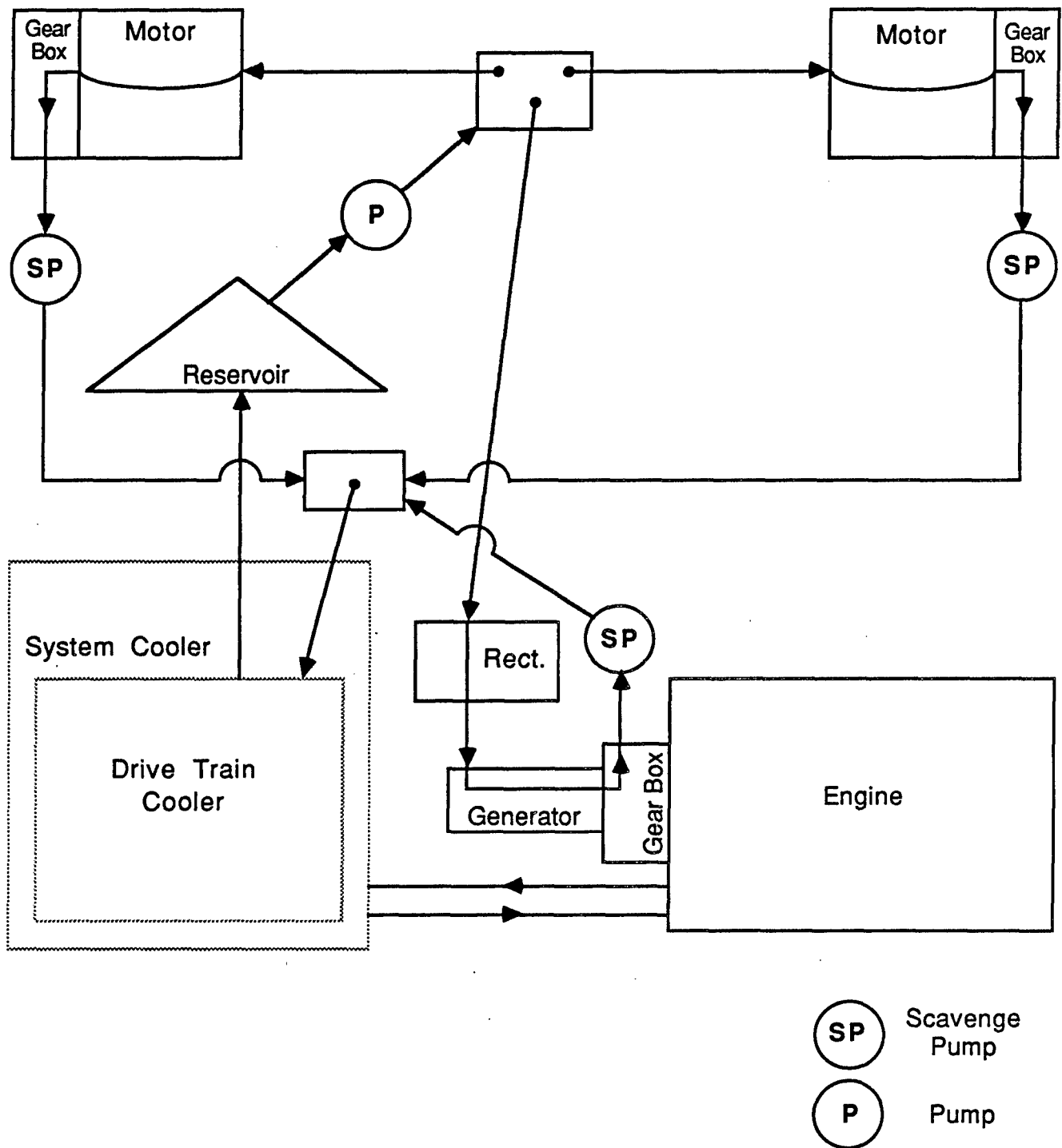


Figure 5.4-27. Cooling System Flow Diagram for ACEC Concept

TABLE 5.4-42. 19.5 TON ACEC CONCEPT(I-5)
COOLING SYSTEM WEIGHT AND VOLUME ESTIMATES

DESCRIPTION	QUANTITY	UNIT VOLUME		SYSTEM VALUE		UNIT WEIGHT		SYSTEM WEIGHT	
		IN ³		IN ³		lb		lb	
Scavenge Pump	3	6.5		19.5		5		15	
Scavenge Pump Motor	3	161		483		18		54	
Manifold	1	67.5		67.5		7.1		7.1	
Check Valve	3	22		66		5		15	
Pressure Valve	2	22.5		45		1.5		3	
Filters	2	305.3		610.3		13		26	
Dump and By Pass Valves	3	inline		-		-		-	
Gear Pump	2			212				40	
Reservoir	1	915		915		8		8	
Fans and Drives	3			725				190	
Electrical Cooler	1	2520		2520		50		50	
Engine Cooler	1	7680		7680		202		202	
Cooling Medium	9 gal	-		-		63		63	
Total				13343.8				673.1	

TABLE 5.4-43. DUAL PATH TRANSMISSION POWER DISTRIBUTION
19.5 TON UNIQUE MOBILITY CONCEPT

<u>Vehicle Speed</u>	<u>Mechanical Power</u>	<u>Electrical Power</u>
0	0	0
5	0	192
10	0	192
15	0	192
20	148	44
25	119	73
30	99	93
35	85	107
40	74	118
45	66	126

Total Horsepower Required is 192 H.p.

TABLE 5.4-44. TRANSMISSION EFFICIENCY AND HEAT REJECTION FOR
UNIQUE MOBILITY CONCEPTS

	<u>BASE</u>		<u>MAX.</u>
Vehicle Speed (mph)	5	15	45
Motor rpm	1119	3360/759	7480
	<u>Elect.</u>	<u>Elect/Mech.</u>	<u>Elec/Mech.</u>
Generator Eff.	93.5	93.5-92.0	93.5-92.0
Transfer Case Eff.	98	93.5-92.0	93.5-92.0
Rectifier	98	98-92.0	98-92.0
Motor Controller	98	98-92.0	98-92.0
Motor	96	96-92.0	96-92.0
Single Speed G.B.	98	98-92.0	98-92.0
System Efficiency	82.7	82.7/89.8	85.9
Heat Rejection Rate (BTU/MIN)	3134	3134/1848	2554

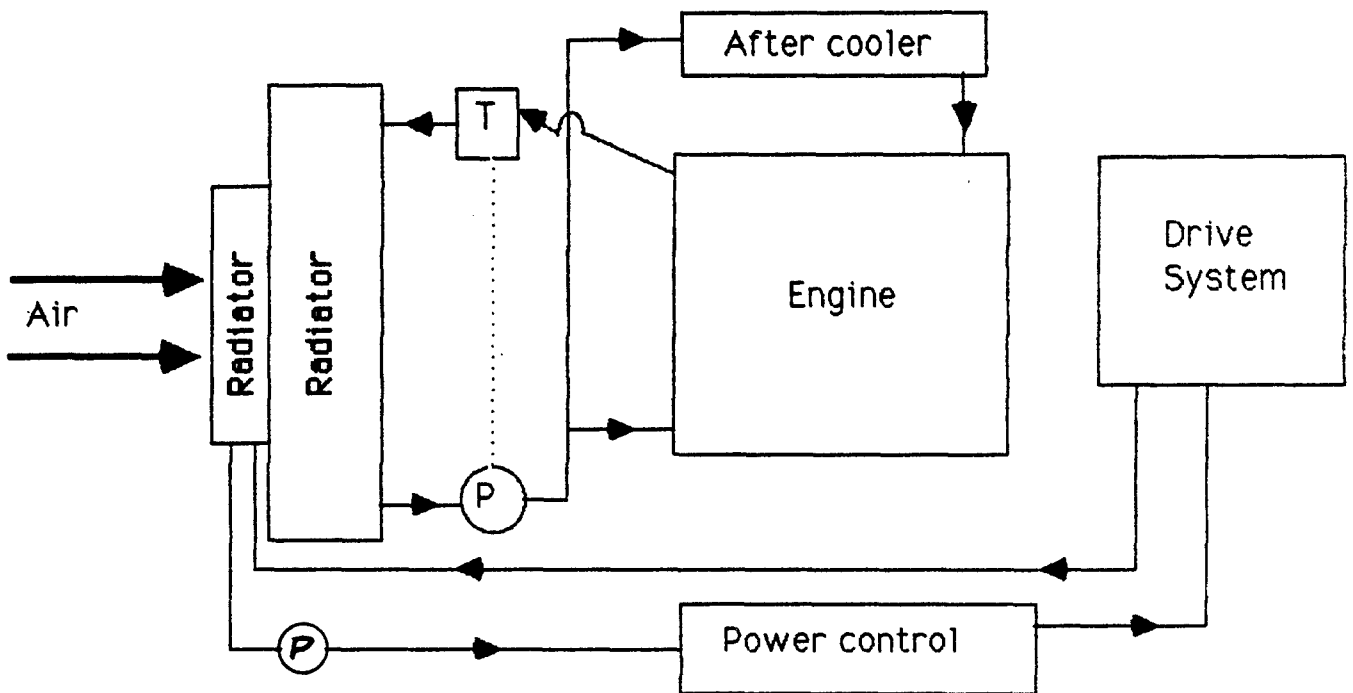


Figure 5.4-28. Cooling System for Unique Mobility Concepts

TABLE 5.4-45. HEAT EXCHANGER CHARACTERISTICS FOR
UNIQUE MOBILITY CONCEPTS

		19.5 TON	40 TON
DRIVE SYSTEM COOLER			
TOIL OUT	(°F)	200	200
TOIL IN	(°F)	29	29
TAIR IN	(°F)	125	125
TAIR OUT	(°F)	133	138
AIR VELOCITY	(FPM)	2000	2000
OIL FLOW RATE	(GPM)	24	48
HEAT REJECTION	(BTU/MIN)	2497	4994
SIZE	(INCHES)	40x36x1.5	42x40x3
TUBE AND MOTOR COOLING			
AIR FLOW	(FT ³ /IN)	500	1000
REQUIRED PER MOTOR			
TAIR	(°F)	39	39
HEAT REJECTION	(BTU/MIN)	318	636
RATE PER MOTOR			
SYSTEM COOLER			
TWATER IN	(°F)	230	230
TWATER OUT	(°F)	214	207
TAIR IN	(°F)	133	138
TAIR OUT	(°F)	193	185
WATER FLOW RATE	(GPM)	120	160
AIR VELOCITY	(FPM)	2000	2000
HEAT REJECTION	(BTU/MIN)	14000	27000
SIZE	(INCHES)	32x32x7.5	50x51x7.5

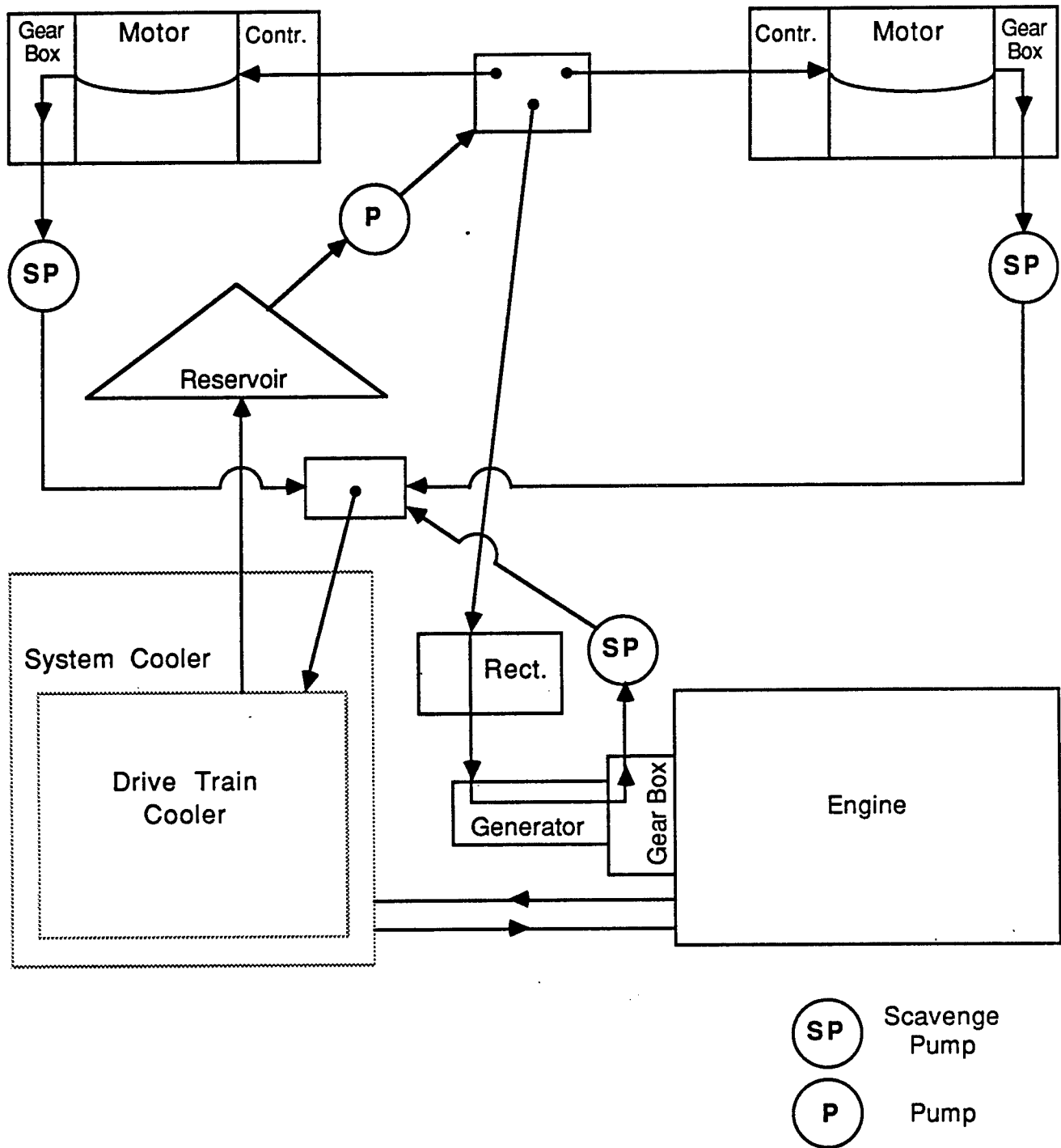


Figure 5.4-29. Cooling System Flow Diagram for Unique Mobility Concepts

TABLE 5.4-46. 19.5 TON UNIQUE MOBILITY IV-2 CONCEPT (I-5)

COOLING SYSTEM WEIGHT AND VOLUME ESTIMATES

DESCRIPTION	QUANTITY	UNIT VOLUME		SYSTEM VALUE		UNIT WEIGHT		SYSTEM WEIGHT	
		IN ³		IN ³		lb		lb	
Scavenge Pump	3	6.5		19.5		5		15	
Scavenge Pump Motor	3	161		483		18		54	
Manifold	1	67.5		67.5		7.1		7.1	
Check Valve	3	22		66		5		15	
Pressure Valve	2	22.5		45		1.5		3	
Filters	2	305.3		610.3		13		26	
Dump and By Pass Valves	3	inline		-		-		-	
Gear Pump	2			212				40	
Reservoir	1	915		915		8		8	
Fans and Drives	3			725				190	
Electrical Cooler	1	2520		2520		50		50	
Engine Cooler	1	7680		7680		202		202	
Cooling Medium	9 gal	-		-		63		63	
Total				13343.8				673.1	

TABLE 5.4-47. 40 TON UNIQUE MOBILITY CONCEPT (IV-2)

COOLING SYSTEM WEIGHT AND VOLUME ESTIMATES

DESCRIPTION	QUANTITY	UNIT VOLUME		SYSTEM VALUE		UNIT WEIGHT		SYSTEM WEIGHT	
		IN ³		IN ³		lb		lb	
Scavenge Pump	3	6.5		19.5		5		15	
Scavenge Pump Motor	3	161		483		18		54	
Manifold	1	67.5		67.5		7.1		7.1	
Check Valve	3	22		66		5		15	
Pressure Valve	2	22.5		45		1.5		3	
Filters	2	305.3		610.3		13		26	
Dump and By Pass Valves	3	inline		-		-		-	
Gear Pump	2			366				69	
Reservoir	1	1728		1728		22		22	
Fans and Drives	3			965				240	
Electrical Cooler	1	5040		5040		82		82	
Engine Cooler	1	21068		21068		551		551	
Cooling Medium	14 gal	-		-		98.3		98.3	
Total				30458.3				1182.4	

5.4.10 Propulsion System Control Logic

The electric propulsion "system" consists of the prime mover, the electric generator, the power conditioning unit(s), the traction motor(s), the torque multiplication/speed reduction gearbox(es), and the final drives. The propulsion system is controlled by an electronic control unit (ECU) which in turn is controlled by the vehicle driver. The electronic control unit generates all system control signals; receives all system input, feedback, and monitoring signals; and coordinates all system protection functions. The electronic control unit receives its primary control-input signals to accelerate, brake, and steer from the vehicle driver. It then translates these driver generated signals into corresponding electronic signals which control the prime mover input fuel rate, the power electronic devices within the drivetrain power conditioning units, and the electric or hydraulic actuators within brake and gear shifting units. The detailed operation of the propulsion system is thus determined by the control logic of the electronic control unit. In this section we describe the control logic for the three best electric drive concepts determined by our concept screening methodology. The layouts of these three best concepts are described in sections 5.4.1 through 5.4.5 of this report. Of particular note is the choice of a permanent magnet synchronous generator and a series connection scheme for the traction motor PCU's (or just the traction motors in the case of the ACEC concept) for all three "best" concepts. This choice enables a common control scheme to be specified for all three concepts. This common control scheme is described in the remainder of this section.

A driver input command for more tractive effort results in an ECU command to the traction motors for more output torque. In the case of an AC traction motor, this ECU command increases the "torque angle" of the machine. Torque angle refers to the angular position of the synchronously rotating stator magnetic field (created by the stator AC currents) relative to the rotor magnetic field (created by the permanent magnets). The maximum torque position occurs whenever the stator and rotor magnetic fields are aligned in positions at 90° by the commutator/brush geometry so increased torque is attained by an increase in the field flux. In either the AC or DC traction

motors, increased traction motor output results in a corresponding increase in generator output and therefore a greater load on the prime mover. The input fuel rate control logic senses this increased load and raises the input fuel rate to compensate it. The logic is such that the prime mover is always operated at its maximum efficiency point for a given level of steady-state output.

A driver input command for a steer maneuver results in an ECU command to the traction motors for differential output torque. This command can be an addition to a steady state or an increased traction command. Differential torque is attained via differential torque angles in AC machines or differential field fluxes in DC machines. If the steer command is of sufficient magnitude the inside track traction motor will become a generator and transfer the inside track "brake" power through the electric drivetrain to the outside track motor. If the steer maneuver results in an increased total traction motor output there will be a corresponding increase in the main generator output and therefore an increased prime mover load. As in the increased traction command action, this increase in prime mover load is compensated by an increase in the prime mover fuel rate. Again, the prime mover is operated at its maximum efficiency point for the given level of steady-state load.

To give the detailed control logic of the drivetrain, models must first be developed for the individual elements. These models are given in several standard electrical engineering texts so their derivation is only outlined here. The models needed are for PM AC machines operated with current source controlled converters at their terminals and for separately excited DC machines. These models are discussed in the following paragraphs.

A permanent magnet synchronous AC machine develops an AC internal (back emf) voltage proportional to machine speed (ω). In the ideal case, this machine would operate with no winding resistance or output inductance. Figure 5.4-30 depicts a schematic of this machine with a current source controlled converter at the terminals.

Referring to this figure, the converter DC terminal voltage V_{DC} is proportional to the AC machine internal voltage and to the cosine of the "firing

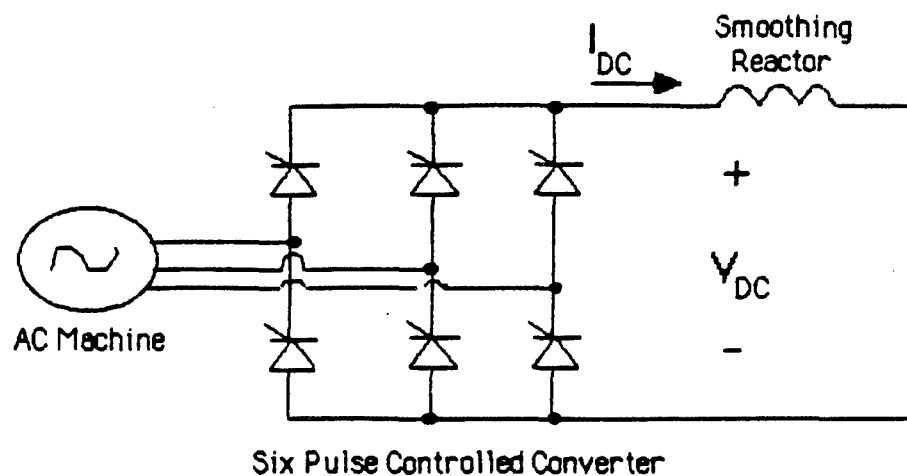


Figure 5.4-30. PM AC Machine with Controlled Converter

angle," $\cos \alpha$, of the converter. The firing angle α is the electrical angle between a reference point on the machine internal voltage waveform and the time of firing of the corresponding power electronic device (shown as SCR's in figure 5.4-30) in the controlled converter. The DC output voltage V_{DC} for a realistic AC machine is degraded from the ideal value by a component that is proportional to the DC output current- I_{DC} , the machine speed, and the output inductance of the machine. Presence of output inductance in the machine winding effectively forces periods of simultaneous conduction of two switching elements in either the top or bottom half of the six-pulse bridge shown in figure 5.4-30; whereas the normal mode of conversion is a single element conducting in either the top or bottom half at any one time. This simultaneous conduction period is termed an overlap period. Another component which degrades the DC output voltage is the winding resistance of the machine. This component is also proportional to the DC output current I_{DC} . For a generator controlled converter, this can be expressed in equation form as:

$$V_{DC} = E_g W_g \cos \alpha - (W_g R_{ug} + R_{sg}) I_{DC}$$

E_g is the machine internal voltage constant, W_g is the generator speed, R_{ug} is the overlap resistance per unit speed (proportional to machine winding output inductance), and R_{sg} is proportional to machine winding resistance. This equation can be represented by an equivalent DC electrical circuit shown as figure 5.4-31.

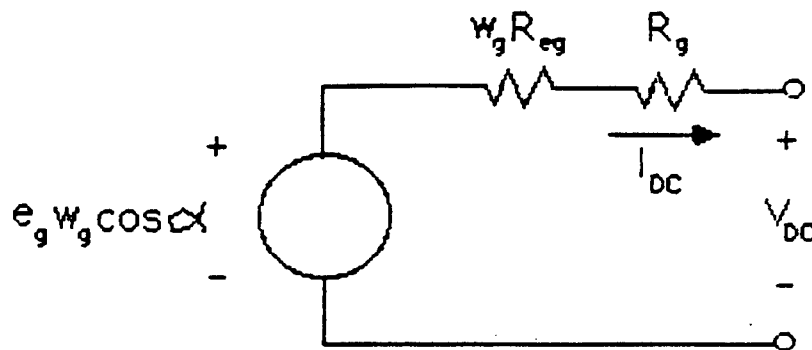


Figure 5.4-31. DC Equivalent Circuit of a Permanent Magnet Generator
Operating into a Current Source Controlled Converter

The presence of the voltage drop due to converter overlap is not a power loss voltage drop such as that due to the winding loss resistor R_{sg} , and therefore it cannot be counted in efficiency calculations. It must be counted, however, in the power production calculations, i.e., as the developed or air-gap power P_g of the generator given by:

$$P_g = (E_g W_g \cos \alpha - W_g R_{ug} I_{DC}) I_{DC}$$

The machine/converter efficiency is thus given by:

$$\text{Generator/converter efficiency} = \frac{P_g - R_{sg} I_{DC}^2}{P_g}$$

For motor operation, it is convenient to reverse the reference direction of the DC current I_{DC} and define an inverter firing angle $\beta = 180^\circ - \alpha$. The resulting equation is:

$$V_{DC} = (W_g R_{um} + R_{sm}) I_{DC} + E_m W_m \cos \beta$$

E_m is the machine internal voltage constant, W_m is the motor speed, R_{um} is the overlap resistance per unit speed (proportional to winding output inductance) and R_{sm} is proportional to machine winding resistance. This equation can be represented by the equivalent DC electrical circuit shown in Figure 5.4-32.

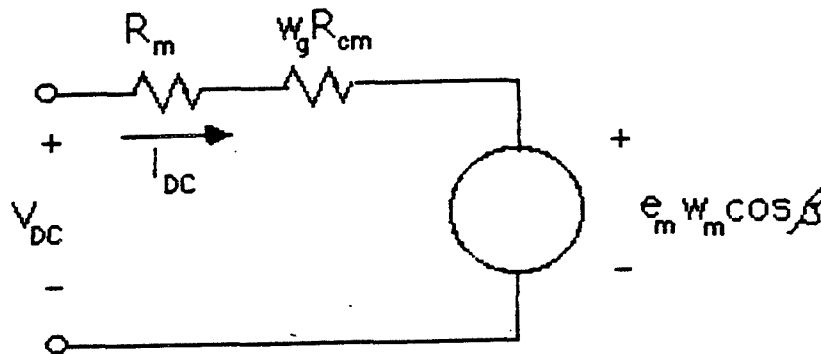


Figure 5.4-32. DC Equivalent Circuit of a Permanent Magnet Motor Operated from a Current Source Controlled Converter

As with the generator, the equivalent resistance $W_m R_{um}$ does not degrade efficiency so the motor output shaft power is obtained from:

$$P_m = (E_m W_m \cos\beta + W_m R_{um} IDC) IDC$$

The motor/converter efficiency is expressed by:

$$\text{Motor/generator efficiency} = \frac{P_m}{P_m + R_{sm}(IDC)^2}$$

Unlike a generator/converter the motor/converter voltage source "firing angle", β , cannot be pushed arbitrarily close to zero degrees. The overlap process which occurs immediately after firing, requires a finite amount of time for completion. If β is too small, this overlap process will spill over into the next firing period and cause what is known as a commutation failure which results in an effective short circuit as the inverter input. For this reason, β is generally restricted to be at least as large as 30 electrical degrees. This insures that the converter will run as an inverter when needed and in a controlled manner.

Separately excited DC machines have their field flux (or field excitation) supplied by a "separate" source of DC current. Typically, at full field flux, this separate source must supply only one to two percent of the full machine output rating to the field winding. The internal machine armature voltage or back emf, is proportional to the field flux and to the machine speed, and as with the AC machine, there is a winding resistive loss voltage drop between the machine internal voltage and the terminal voltage. In equation form and with motor notation, this effective voltage can be expressed as:

$$VDC = IDC R_{sm} + K_a \phi_f W_m$$

where IDC is the DC current, R_{sm} is the winding resistance, K_a is the machine internal proportionality constant, ϕ_f is the field flux and W_m is the shaft speed. The equivalent circuit which represents this equation is given in Figure 5.4-33.

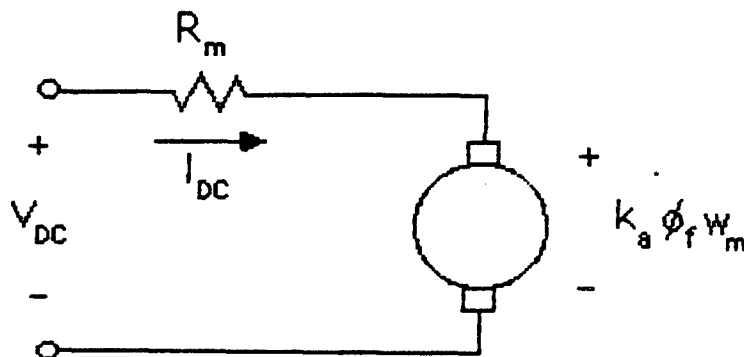


Figure 5.4-33. DC Equivalent Circuit of a DC separately Excited Machine

By reversing the polarity of the field flux, this machine becomes a generator and delivers power to the DC network. As a motor, the efficiency is:

$$\text{Motor efficiency} = \frac{K_a \phi_f W_m}{K_a \phi_f W_m + R_{sm} I_{DC}}$$

While as a generator, the efficiency is:

$$\text{Generator Efficiency} = \frac{K_a \phi_f W_m - R_{sm} I_{DC}}{K_a \phi_f W_m}$$

5.4.10.1 Electric Machine/PCU Scheduling.

The machine and PCU models developed in the previous section are combined into complete electric drivetrains in Figures 5.4-34 and 5.4-35. Figure 5.4-34 is the generic equivalent circuit for the Garrett 19.5 Ton and 40 Ton Configura-

tion I concepts and for the Unique Mobility 19.5 Ton and 40 Ton Configuration IV concepts. Figure 5.4-35 is the equivalent circuit of the ACEC 19.5 Ton Configuration I concept. One motor in each drivetrain is designated as the "outside" motor and the other as the "inside" motor. These designations are for control descriptions only.

In an actual system, either motor, depending on the direction of a particular turn, can assume the role of the outside machine, while the other would be the inside machine. The similarity between the AC and DC drive concepts should be noted. In particular, the similar functions of the AC machine inverter firing angle control, $\cos\beta$, and DC machine field flux control, ϕ_f should be noted. In fact, a completely generic electric drivetrain equivalent circuit can now be defined. One circuit will serve to describe the workings of both the AC drive and the DC drive concepts. This generic circuit is shown in Figure 5.4-36. In comparison with the AC drive circuit shown in Figure 5.4-34, the control variable ψ_o is identified with the cosine of the inverter firing angle, and the resistor R_{sm} with the total AC resistance $R_{sm} + W_m R_{um}$. If the DC drive circuit of Figure 5.4-35, is to be compared, then the proportionality constant E_m is identified with the armature constant K_a and the control variable ψ_i is identified with the field flux ϕ_f . Of course in an actual drive there are physical limitations on $\cos\beta$, $-1 \leq \cos\beta \leq \cos 30^\circ$, and over voltage and saturation limits ϕ_f , $-\phi_{f \max} \leq \phi_f \leq \phi_{f \max}$. These limits can be managed in the actual circuits by placing appropriate hard limits in the ECU control logic. The intent here is to show only the basics of the control scheme. Assuming simple proportional control, the variable ψ has two components. These are:

$$\psi_v = K_t \times TE \text{ (demand)}$$

and

$$\psi_{\Delta v} = K_{\Delta v} \times \Delta v \text{ (demand)}$$

Thus

$$\psi_o = \psi_v + \psi_{\Delta v}$$

and

$$\psi_i = \psi_v - \psi_{\Delta v}$$

Where K_t is the gain constant for the tractive effort control and $K_{\Delta V}$ is the gain constant for differential speed, ΔV , or steer control. The demand tractive effort signal, TE (demand) is a driver input, such as that from an accelerator foot pedal. The demand differential speed signal, ΔV (demand), is also a driver input, such as that from a steering wheel. It should be noted that both TE (demand) and ΔV (demand) can be negative, indicating desired reverse speed and an opposite side turn, respectively.

The DC current IDC is maintained at a level that is proportional to prime mover speed. This is accomplished by control of the generator controlled rectifier firing angle, i.e., variation of $\cos \alpha$.

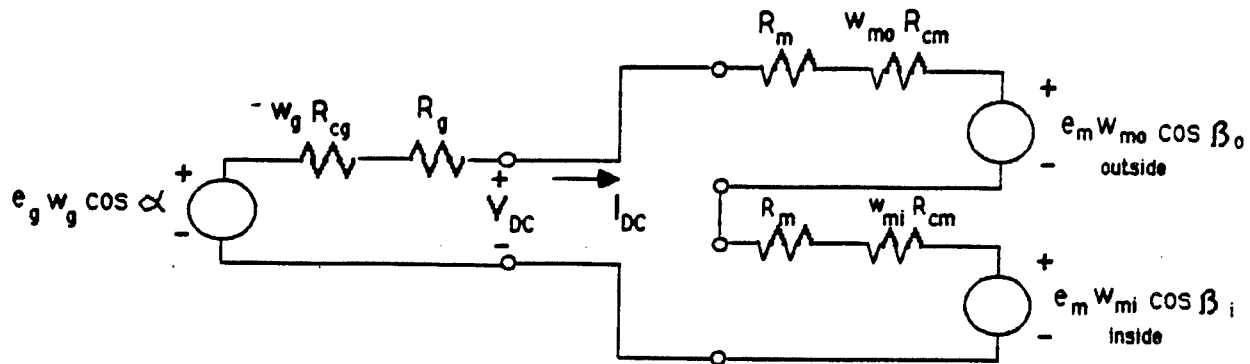


Figure 5.4-34. AC Equivalent Circuit of ACEC Drive

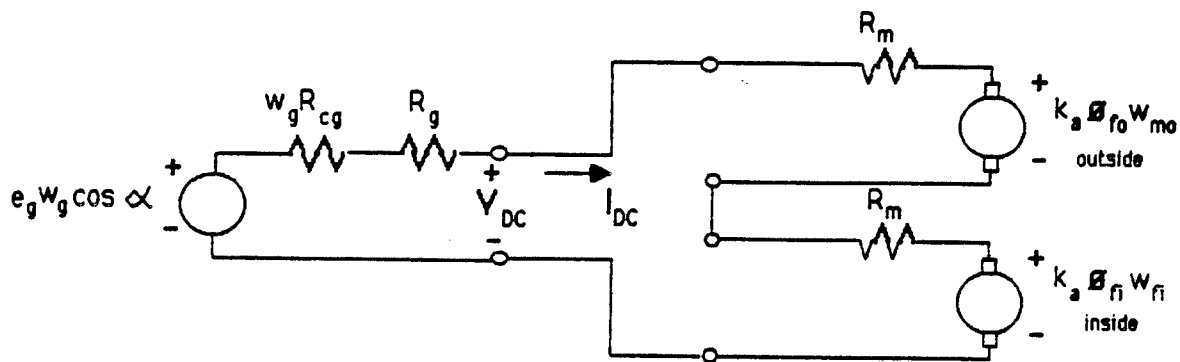


Figure 5.4-35. DC Equivalent Circuit of Garrett and Unique Mobility Drives

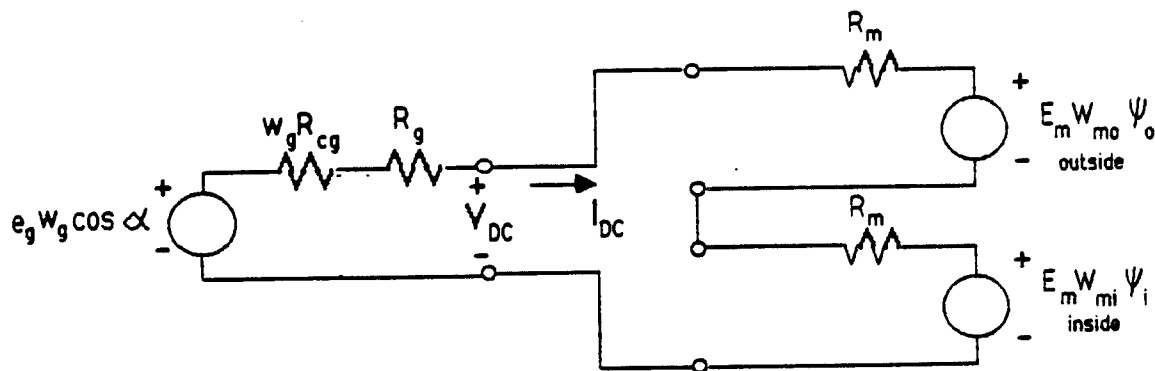


Figure 5.4-36. Generic DC Equivalent Circuit Suitable for ACEC, Garrett, and Unique Mobility Drives

The DC current is expressed by:

$$I_{DC} \text{ (desired)} = I_{DC_{max}} W_g / W_{g_{max}}$$

Therefore, the rectifier firing angle can be expressed as:

$$\cos \alpha = \frac{I_{DC} \text{ (desired)} \times (2 R_{sm} + R_{sg} + W_g R_{ug}) + E_m (W_{mo} + W_{mi})}{E_g W_g}$$

The cosine of the firing angle must be maintained within the following bounds to satisfy physical and inverter operation limitation:

$$\cos(150^\circ) < \cos \alpha < 1$$

The entire electric drive control for a given generator speed, W_g , has now been specified. It remains to translate the control signals to their respective actual variables for an actual AC or DC drive system. An example of the Garrett 19.5 Ton AC system using this method of control is given in section 5.4.11.6 of this report.

5.4.10.2 Engine Scheduling

Since an electric transmission is a pure continuously variable transmission, the prime mover can be scheduled such that it maintains its optimum fuel consumption rate at any given level of steady-state power demand. During non-steady-state operation, i.e., vehicle acceleration and braking, the engine is scheduled for performance rather than economy. It is an ECU function to mesh the performance and economy requirements and to coordinate the prime mover input fuel rate with vehicle dynamics.

To achieve optimum fuel economy in a steady-state condition the ECU must have within its internal "memory" knowledge of the optimum fuel consumption characteristics of the vehicle engine. This information can be displayed graphically in what is commonly referred to as a fuel map. The fuel maps for the two prime movers used in this study, the 500 HP VT-903 and its upgraded 1000 HP version the AD 1000, are given in figures 5.4-37 and 5.4-38. The contours of constant brake specific fuel consumption (BSFC) in units of LB/(HP·HR) in these figures are contours of constant engine efficiency.

From these contours it can be seen that for any given level of engine output power there is one "optimum" operating speed, a speed at which the power is attained at a minimum fuel consumption rate. These optimum engine speeds for the VT-903 and the AD-1000, as a function of output power, are also given in figures 5.4-37 and 5.4-38.

To schedule the engine at its optimum fuel economy point, or its maximum or minimum (engine braking) performance point the ECU will drive the input fuel rate (FR) at a value that is based on the difference between the demand alternator power ($P_{gen\ demand}$) and the optimum alternator power ($P_{gen\ opt}$) which is a function of the present engine speed. At any given time, referred to as the "present", if the demand alternator power is greater than the optimum alternator power at the present engine speed the fuel rate will be increased. If the demand alternator power is less than the present optimum alternator power then the fuel rate will be decreased. If the demand power is equal to the optimum power then the engine is at the optimum speed and the fuel rate will be maintained at its present value. This control, negative

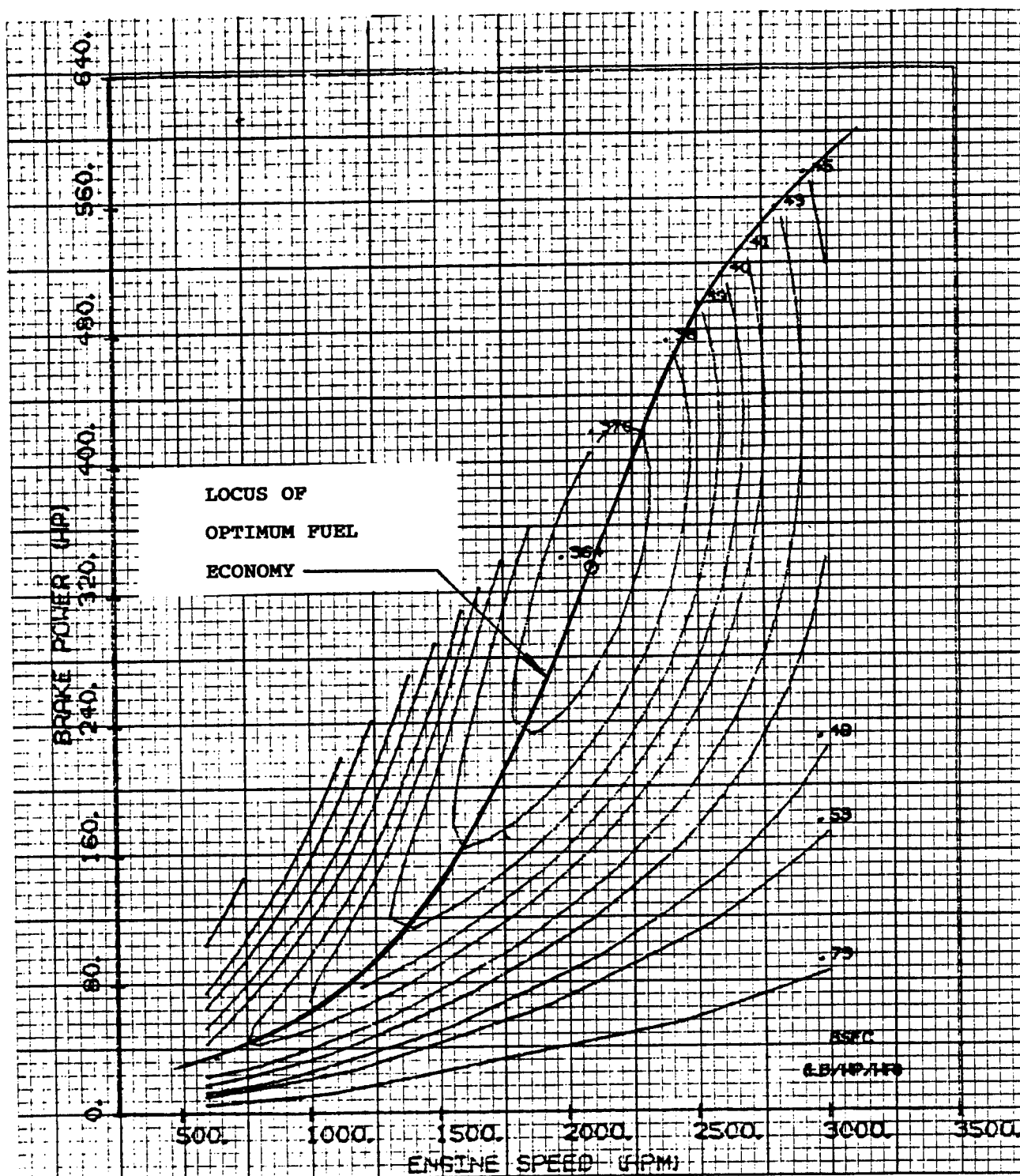


Figure 5.4-37. Fuel Map for VTA-903T Engine

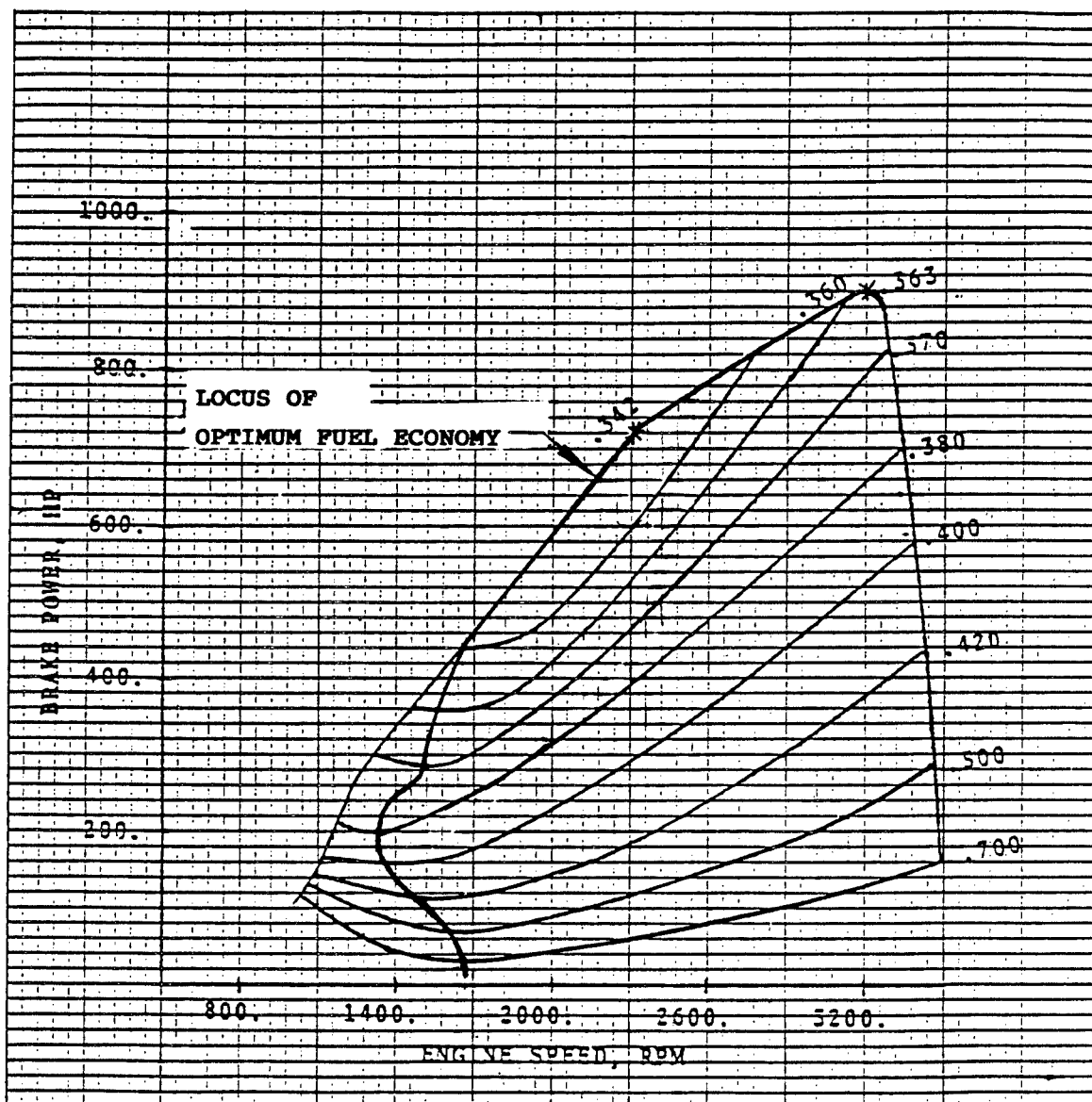


Figure 5.4-38. Fuel Map for AD1000 Engine

feedback, will maintain optimum fuel economy in the steady-state but still allow for maximum dynamic performance operation, by continued operation at limiting demand power operating points. For example, during a dash the demand alternator power would be at its maximum value (rated value) throughout the dash, thus driving the input fuel rate to its maximum value, while during engine braking, the demand power would be negative, thus driving the input fuel rate to its minimum value. A block diagram showing this fuel rate control is given in figure 5.4-39. In an actual vehicle all computations and logic decisions would be done by the ECU. Also, the type of control shown in figure 5.4-39 is known as proportional control; in an actual vehicle the fuel rate signal could also be made proportional to the time integral of the difference between P_{gen} demand and P_{gen} opt. This would be done to improve the dynamic response of the fuel rate control loop.

5.4.11 Vehicle Performance

The performance of 19.5 and 40.0 ton combat vehicles, incorporating the best electric transmissions concepts from this study, is presented in the following sub-sections. The performance aspects discussed are tractive effort, acceleration, speed on grade, and grade startability. The vehicle performance presented is based on 427 and 855 net horsepower supplied to the transmission concepts at full load conditions for the 19.5 and 40.0 ton vehicles respectively. Also, the performance presented for the 19.5 and 40.0 ton vehicles is based on the following characteristics and assumptions.

- | | |
|----------------------------|-------------------|
| 1. Sprocket Pitch Diameter | 24 Inches |
| 2. Final Drive Ratio | 4:1 |
| 3. Final Drive Efficiency | 98% |
| 4. Rolling Resistance | 100 Pound Per Ton |
| 5. Aerodynamic Resistance | Neglected |
| 6. Hard Surface Condition | |

5.4.11.1 Tractive Effort

The continuous tractive effort obtained from the three best concept applied to the 19.5 and 40.0 ton baseline vehicles are compared to the contract tractive

effort requirements in figures 5.4-40 thru 5.4-44. The Unique Mobility concepts for the 19.5 and 40.0 ton vehicle applications come close to satisfying the tractive effort requirements. These concepts (shown in figures 5.4-42 and 5.4-44) satisfy the requirements above 15 miles per hour, but from zero to 15 miles per hour they are 4 to 6 percent below the requirement. This deficit can be corrected by supplying additional power to the transmission - 25 horsepower to the 19.5 ton vehicle transmission and 15 horsepower to the more efficient 40 ton vehicle transmission. The additional power can be obtained by uprating the engine and/or optimizing the cooling system to reduce cooling fan power requirements.

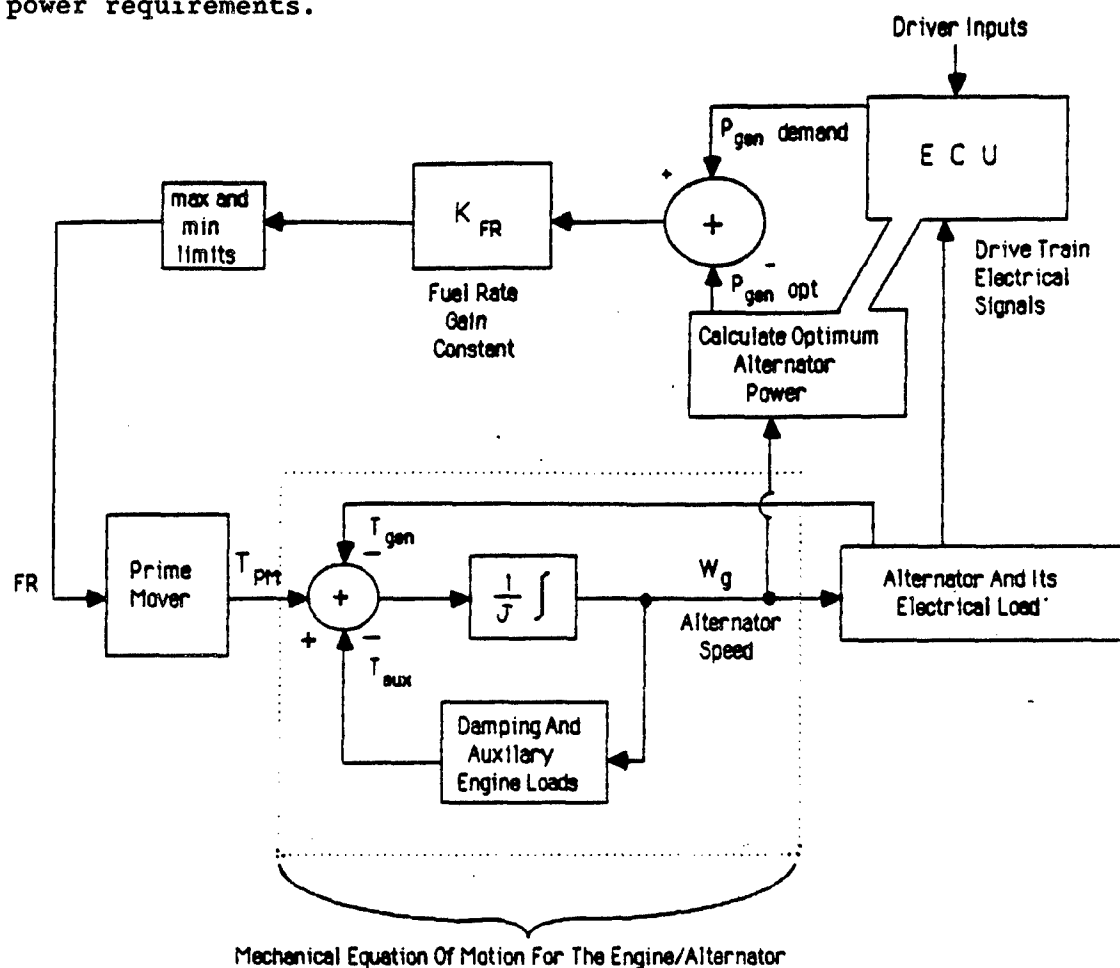


Figure 5.4-39. Control Block Diagram for Engine Fuel-Rate Scheduling

(T_{pm} = prime mover output torque, T_{gen} = alternator load torque, T_{aux} = engine damping and auxiliary load torque, J = combined equivalent engine, transfer case and alternator rotational inertia)

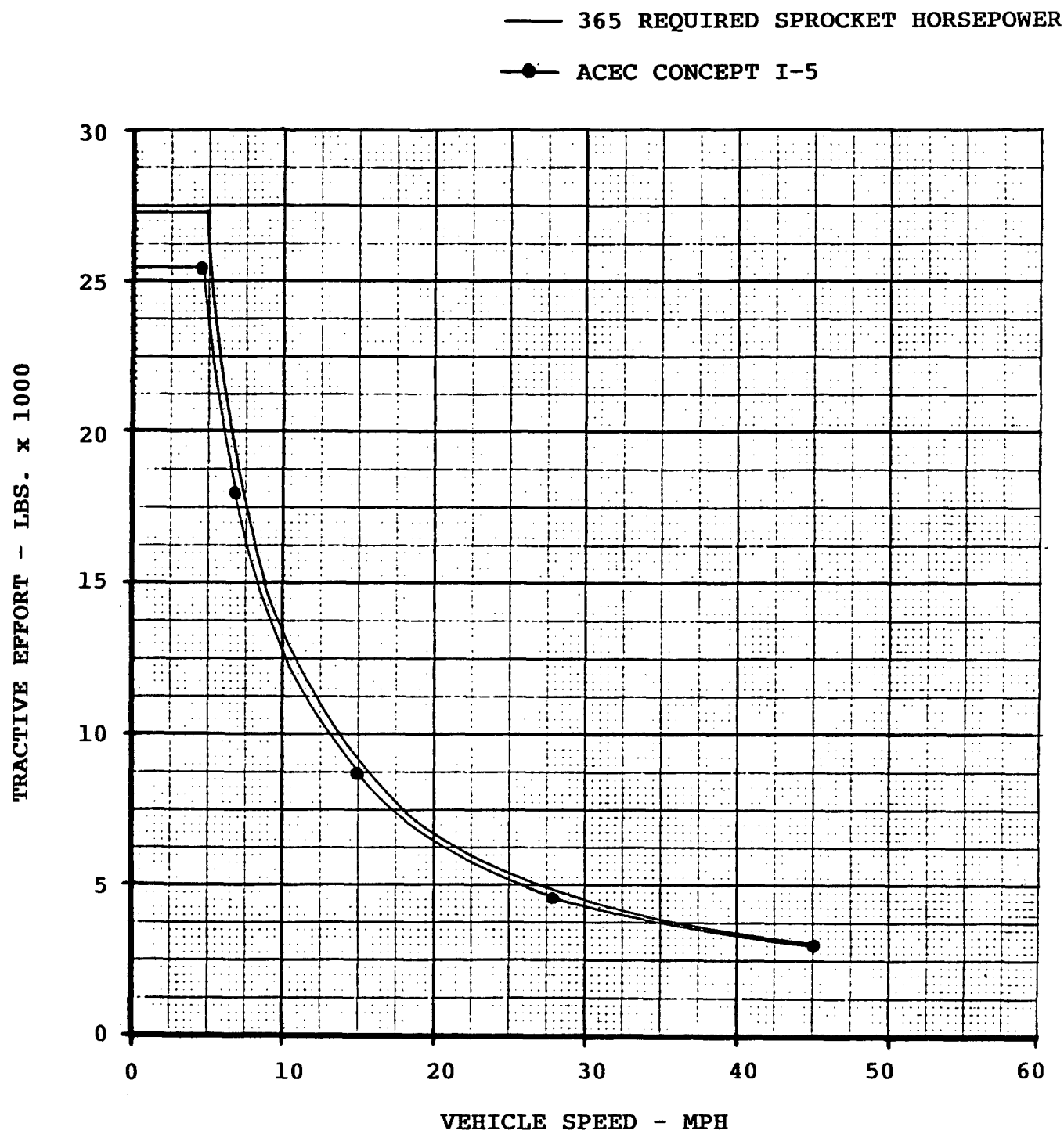


Figure 5.4-40. 19.5 Ton ACEC Concept I-5
Tractive Effort Versus Vehicle Speed

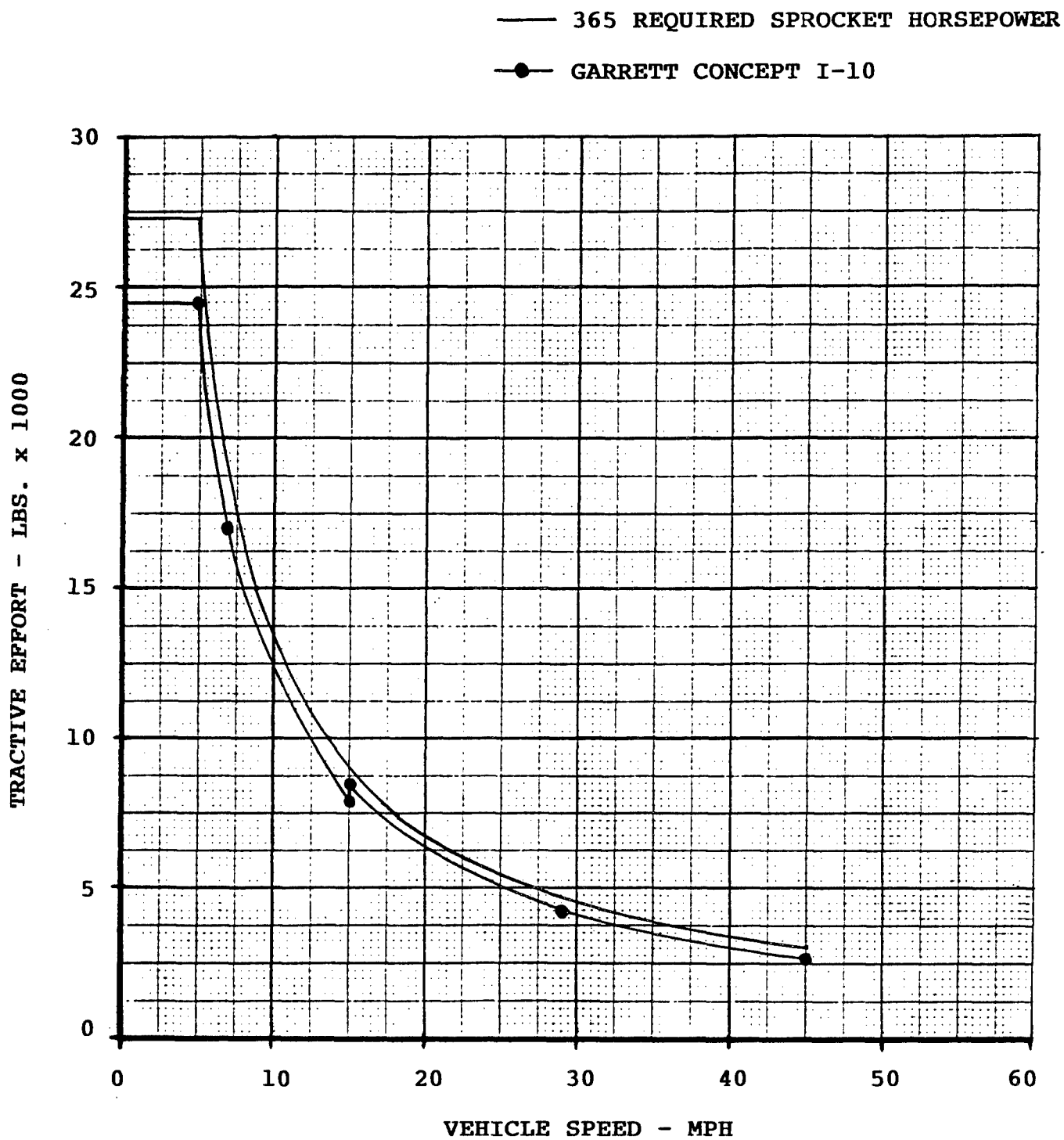


Figure 5.4-41. 19.5 Ton Garrett Concept I-10
Tractive Effort Versus Vehicle Speed

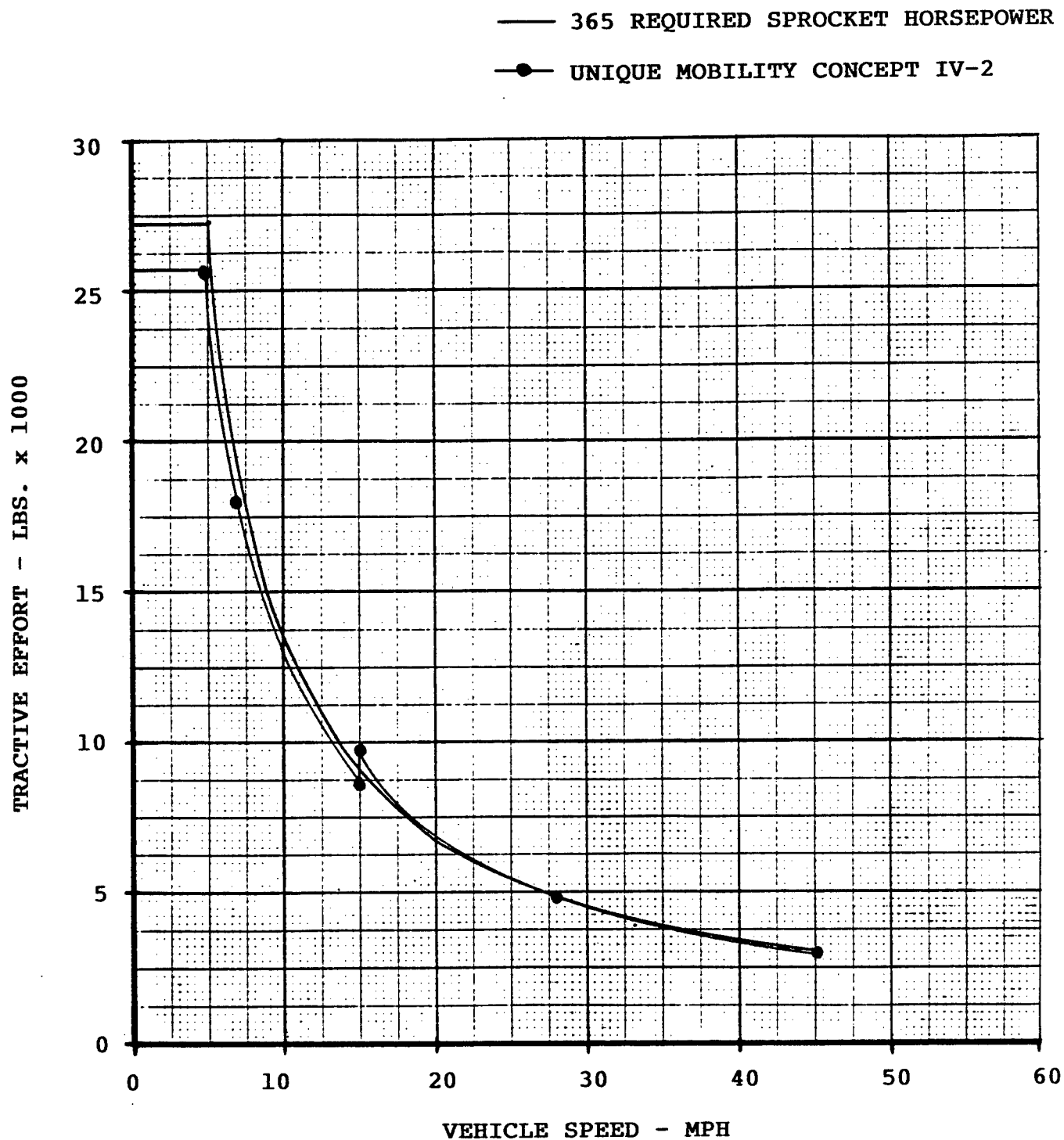


Figure 5.4-42. 19.5 Ton Unique Mobility Concept IV-2
Tractive Effort Versus Vehicle Speed

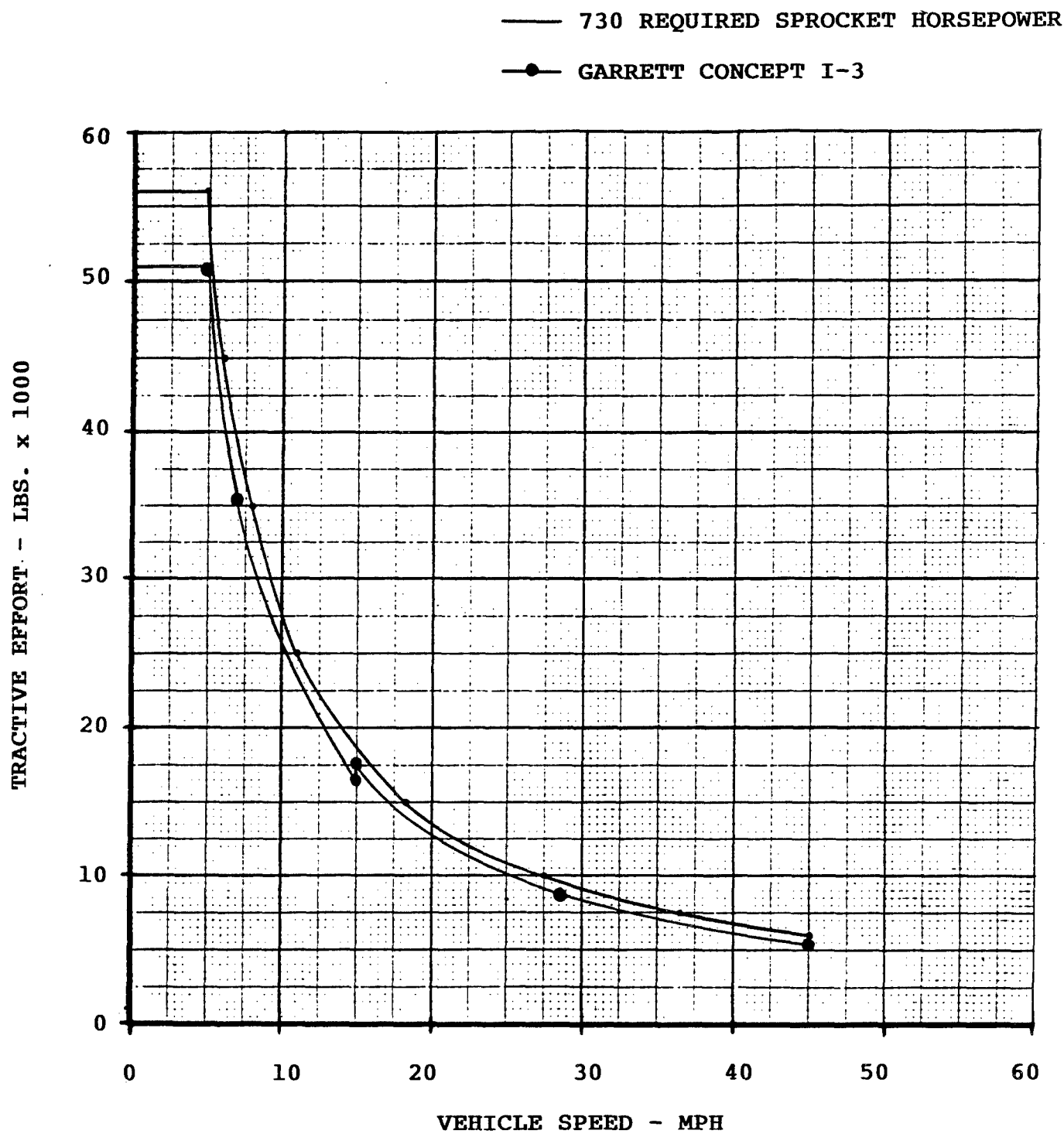


Figure 5.4-43. 40.0 Ton Garrett Concept I-3
Tractive Effort Versus Vehicle Speed

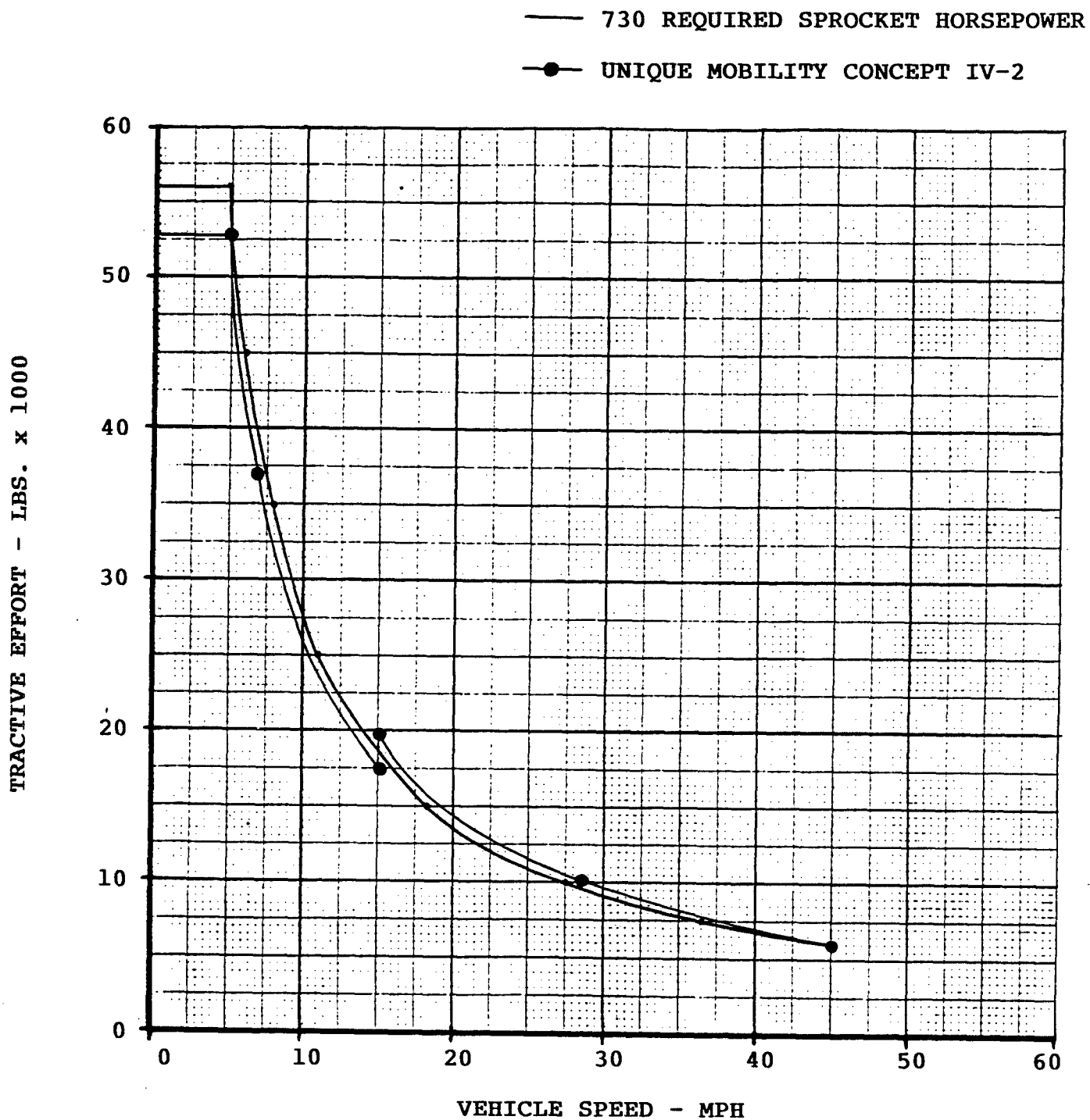


Figure 5.4-44. 40.0 Ton Unique Mobility Concept IV-2
Tractive Effort Versus Vehicle Speed

The 19.5 ton ACEC Concept I-5 (figure 5.4-40) also comes close to satisfying the tractive effort requirement and is 4 to 6 below requirements. Again the deficit can be corrected with an additional 25 horsepower supplied at the transmission input.

The Garrett concepts for 19.5 and 40.0 ton vehicle application (figures 5.4-41 and 5.4-43) fall 9 to 11 percent below the tractive effort requirements and can be corrected by supplying additional horsepower at the transmission of 48 and 36 horsepower respectively.

All of the best three concepts exceed the maximum intermittent traction effort requirement of 1.2 times gross vehicle weight.

5.4.11.2 Acceleration

The acceleration time values for the 19.5 and 40.0 ton baseline vehicles utilizing the three best transmission concepts were determined for the following conditions:

- A. Zero to 20 miles per hour in the forward direction (7 seconds or less required).
- B. Zero to 10 miles per hour in the reverse direction (5 seconds or less required).

The equivalent inertia of the running gear (track, drive sprockets, and road-wheels) used in the determination is 131 lb-ft-sec² for the 19.5 ton vehicle and 285 lb-ft-sec² for the 40.0 ton vehicle. Also the equivalent inertia of the traction motor and gear system is determined as the product of the motor inertia and the square of the reduction ratio of the gear system. For those concepts with gear shift, namely the Garrett, and ACEC concepts a 0.20 second and a 0.50 second shift delay was used respectively. Power from the engine generator set is assumed instantaneously available on demand.

The acceleration times for the 19.5 and 40.0 ton vehicles with electric transmissions starting in low and high gear are presented in table 5.4-48.

The Unique Mobility concepts and the ACEC concept satisfy all acceleration requirements. The Garrett concepts do not satisfy the zero to 20 mile per hour requirement (7 seconds or less) starting in low gear; however, they do satisfy the requirement when starting in high gear.

The best acceleration times for the zero to 20 mile per hour case are 4.50 seconds for the 19.5 ACEC Concept I-5 in high gear and 4.39 seconds for the 40.0 ton Unique Mobility Concept IV-2.

TABLE 5.4-48. ACCELERATION TIMES FOR 19.5 TON
AND 40.0 TON VEHICLES

	Acceleration Time in Seconds			
	0 to 20 MPH		0 to 10 MPH	
	Forward		Reverse	
	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>
<u>19.5 Ton Vehicle</u>				
ACEC Concept I-5	6.98	4.50	1.91	1.17
Garret Concept I-10	8.66	5.12	2.60	1.36
Unique Mobility Concept IV-2	4.85	-	1.11	-
<u>40.0 Ton Vehicle</u>				
Garret Concept I-3	8.17	4.99	2.33	1.29
Unique Mobility Concept IV-2	4.39	-	1.10	-

5.4.11.3 Speed on Grade

The maximum speed on various grades for the 19.5 and 40.0 ton vehicle concepts are presented in table 5.4-49. The effect of air resistance was neglected in the determination of maximum speed.

TABLE 5.4-49. MAXIMUM SPEED ON GRADE
FOR 19.5 AND 40.0 TON VEHICLE

<u>Vehicle Category</u>	<u>Maximum Speed MPH</u>		
	<u>10% Grade</u>	<u>20% Grade</u>	<u>60% Grade</u>
<u>19.5 Ton Vehicle</u>			
ACEC Concept I-5	22.0	13.5	5.5
Garret Concept I-10	21.0	12.5	5.4
Unique Mobility Concept IV-2	24.0	15.0	5.6
<u>40.0 Ton Vehicle</u>			
Garret Concept I-3	21.5	12.5	5.5
Unique Mobility Concept IV-2	24.5	15.0	5.7

All vehicle concepts have good maximum speed on grade values with the unique mobility concepts possessing the highest values.

5.4.11.4 Grade startability

The intermittent capability of the electric transmission concepts provides excellent grade startability for the 19.5 and 40.0 ton vehicle applications. The Garrett and ACEC concepts use traction motors which can produce up to 3 times rated torque for a maximum duration of 30 seconds while the Unique Mobility traction motor can produce 2 times rated torque for short time duty. The maximum intermittent torque (or tractive effort) is available at low vehicle speeds and is dependent on the transmission input power. Table 4.4-50 presents the primary grade startability characteristics of the three best electric drive concepts applied to 19.5 and 40.0 ton vehicles.

TABLE 5.4-50. GRADE STARTABILITY CHARACTERISTICS FOR
19.5 and 40.0 TON VEHICLES

<u>Vehicle Category</u>	Maximum Tractive Effort - Pounds		Initial Acceleration on 60% Grade
	<u>Required</u>	<u>Actual</u>	<u>Ft/Sec²</u>
<u>19.5 Ton Vehicle</u>			
ACEC Concept I-5	46,700	76,500	17.8*
Garret Concept I-10	46,700	73,500	13.11*
Unique Mobility Concept IV-2	46,700	49,000	17.6
<u>40.0 Ton Vehicle</u>			
Garret Concept I-3	96,000	149,000	14.3*
Unique Mobility Concept IV-2	96,000	101,000	17.6

* Starting in Low Gear

The maximum tractive effort provided by the three best concepts in all cases exceed the requirements. Table 5.4-50 presents initial acceleration values for the three best concepts starting from rest on a 60 percent grade. These initial acceleration values include the effects of rolling resistance, grade resistance, and inertia resistance (including translational and rotational inertia). The ACEC and Unique Mobility concepts provide the highest acceleration values. The Garrett concepts have lower initial acceleration values due to high effective rotational inertia produced by the 65.7:1 reduction ratio between traction motor output and final drive output.

5.4.11.5 Propulsion and Steer Schematic with Power Flow Path

This section describes the power flow path of the best three concepts in the propulsion and steer modes. Also the mechanical and electrical components that comprise each concept are illustrated in the figures of this section. Detailed discussion on these components and their significance for performance, weight, volume, reliability, and safety are found elsewhere in this report. However, to help enhance understanding of these power flows, appropriate comments will be included in this section.

Figures 5.4-45 and 5.4-46 show the power flow schematics for the 19.5 ton ACEC concept in low and high gear respectively. The figures show that the traction motors are supplied power (via flexible cables) from the generator so that the conventional mechanical drive line between engine and final drive is eliminated in this concept design. The low and high gear power paths are distinguished by application of the clutches in the planetary gear set of the two speed gearbox shown in the figure.

Figures 5.4-47 and 5.4-48 show the power flow schematics for the 19.5 ton and 40 ton Garrett concepts in the low and high gear respectively. This concept uses two separate planetary gear sets located in the two speed gearbox. Low and high gear power paths are distinguished by application of the clutch patches of the secondary planetary. This concept also eliminates the need for a conventional mechanical drive line.

Figures 5.4-49 and 5.4-50 show the power flow schematics for the 19.5 ton Unique Mobility concept in pure electric mode and in electric-mechanical mode respectively. This dual path concept has independent mechanical and electric power flow paths. When the vehicle is operated in pure electric mode (0 to 15 mph), the mechanical drive shaft is disengaged and tractive power to the drive sprockets is supplied exclusively from the generator to the traction motors. In electric-mechanical mode (15 to 45 mph), power to the sprockets is supplied in parallel by the motor and the mechanical drive shaft with the motor carrying a proportionally greater share of the load under conditions of increasing vehicle speed.

ACEC 19.5 TON
POWER FLOW SCHEMATIC

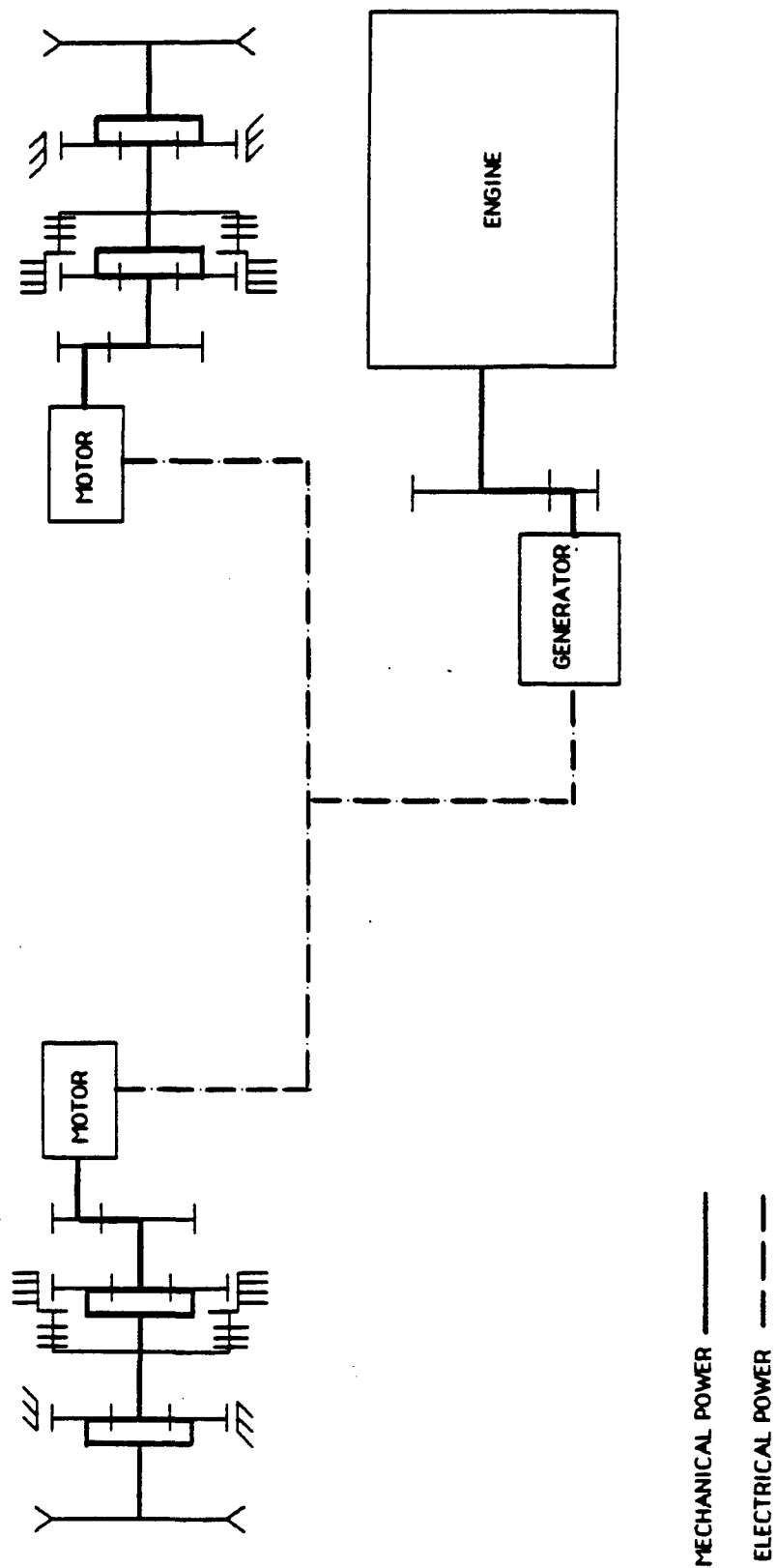


Figure 5.4-45. Power Flow Schematic Low Gear
Power Path, 19.5 Ton ACEC Concept

ACEC 19.5 TON
POWER FLOW SCHEMATIC

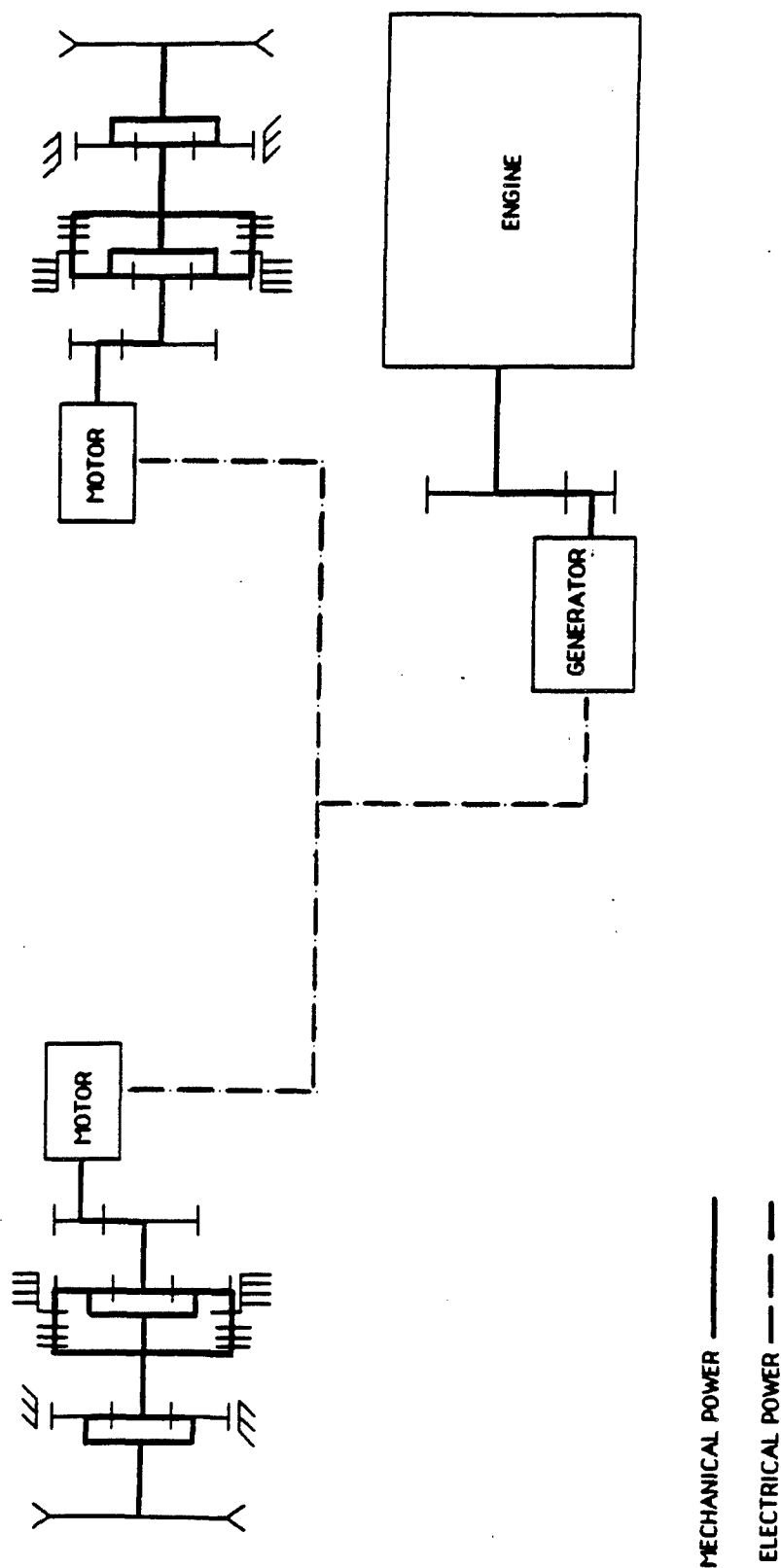


Figure 5.4-46. Power Flow Schematic High Gear Power Path,
19.5 Ton ACEC Concept

GARRETT
POWER FLOW SCHEMATIC

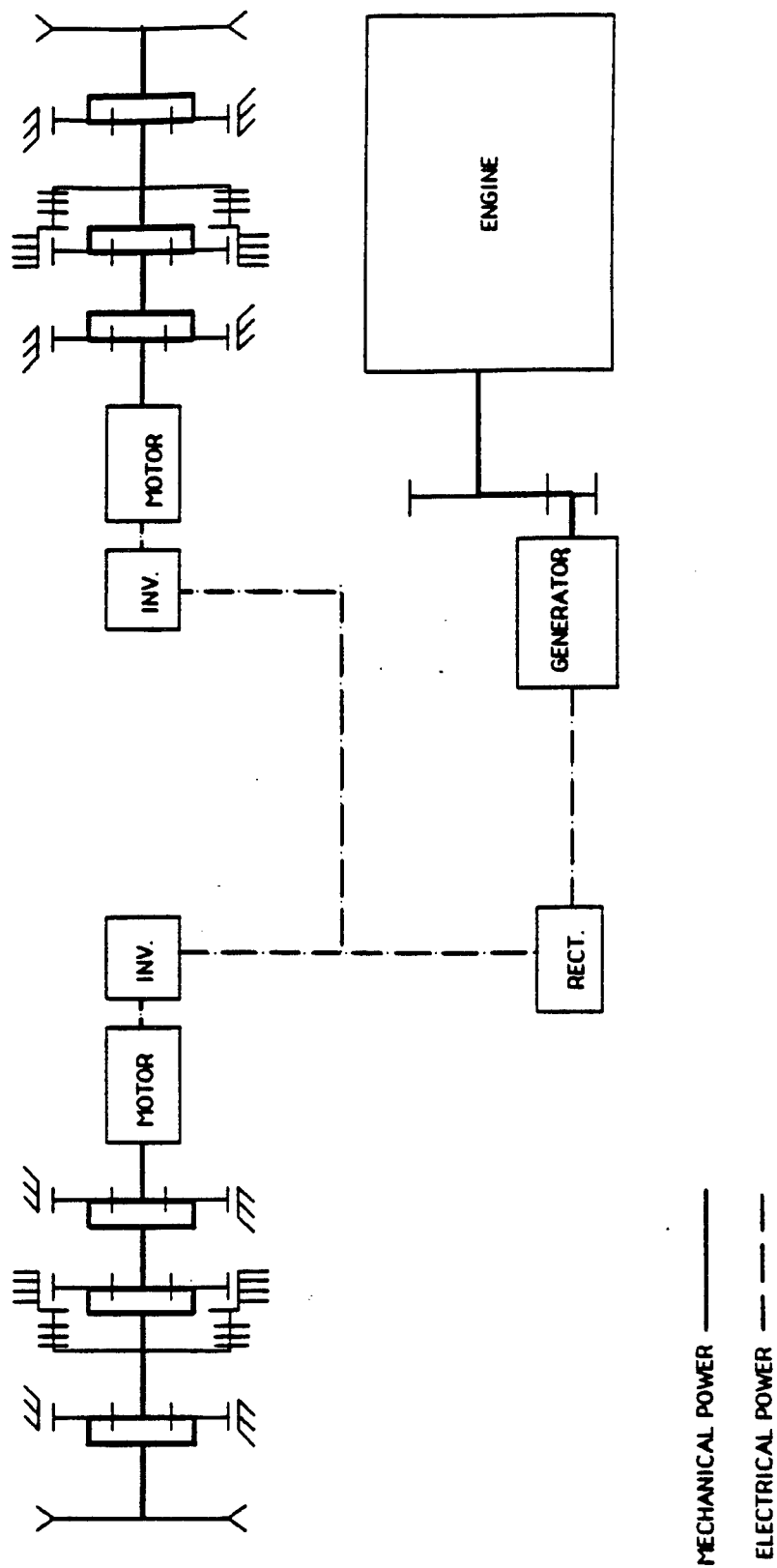


Figure 5.4-47. Power Flow Schematic Low Gear Power Path,
19.5 and 40.0 Ton Garrett Concepts

GARRETT
POWER FLOW SCHEMATIC

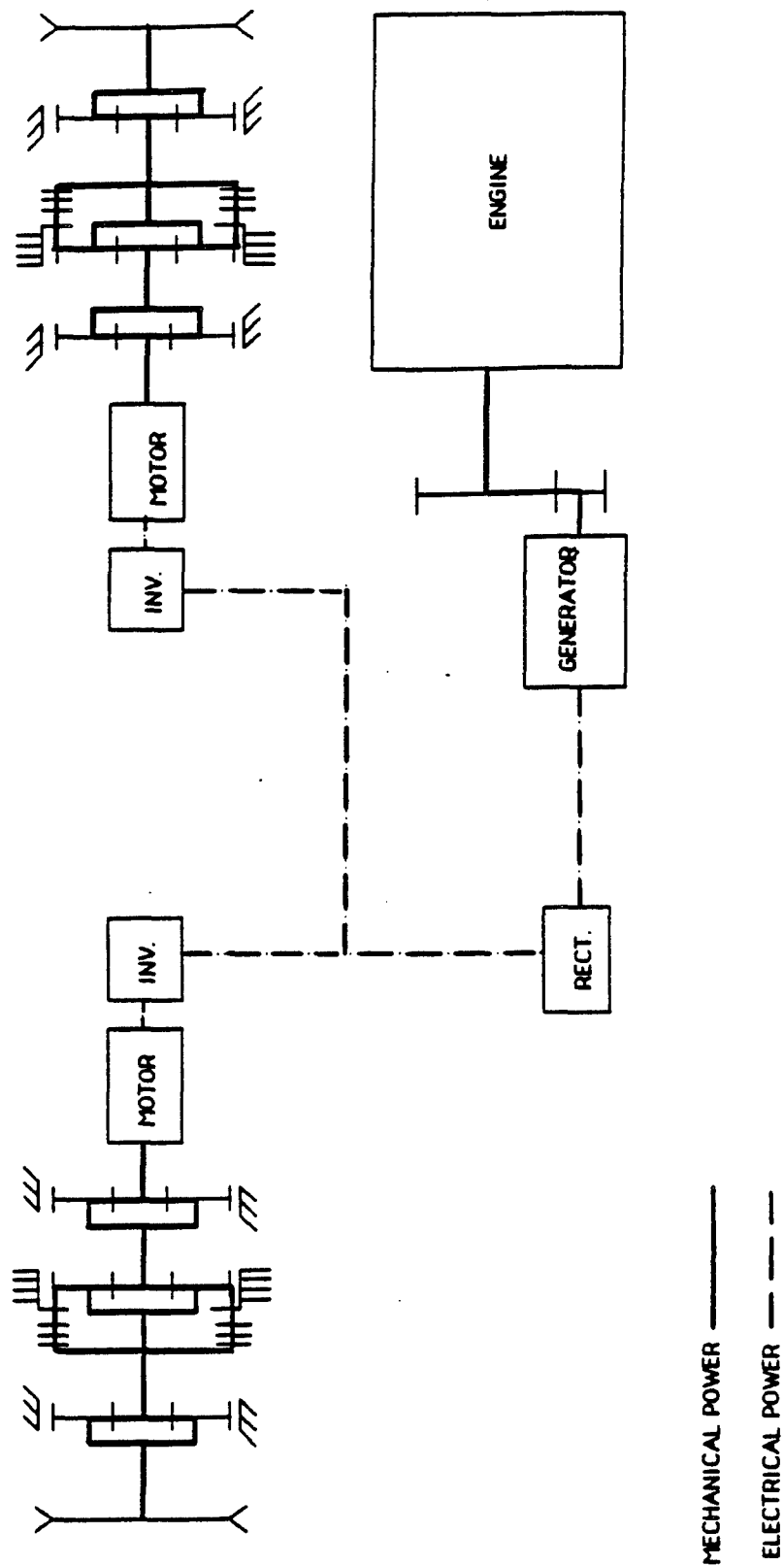
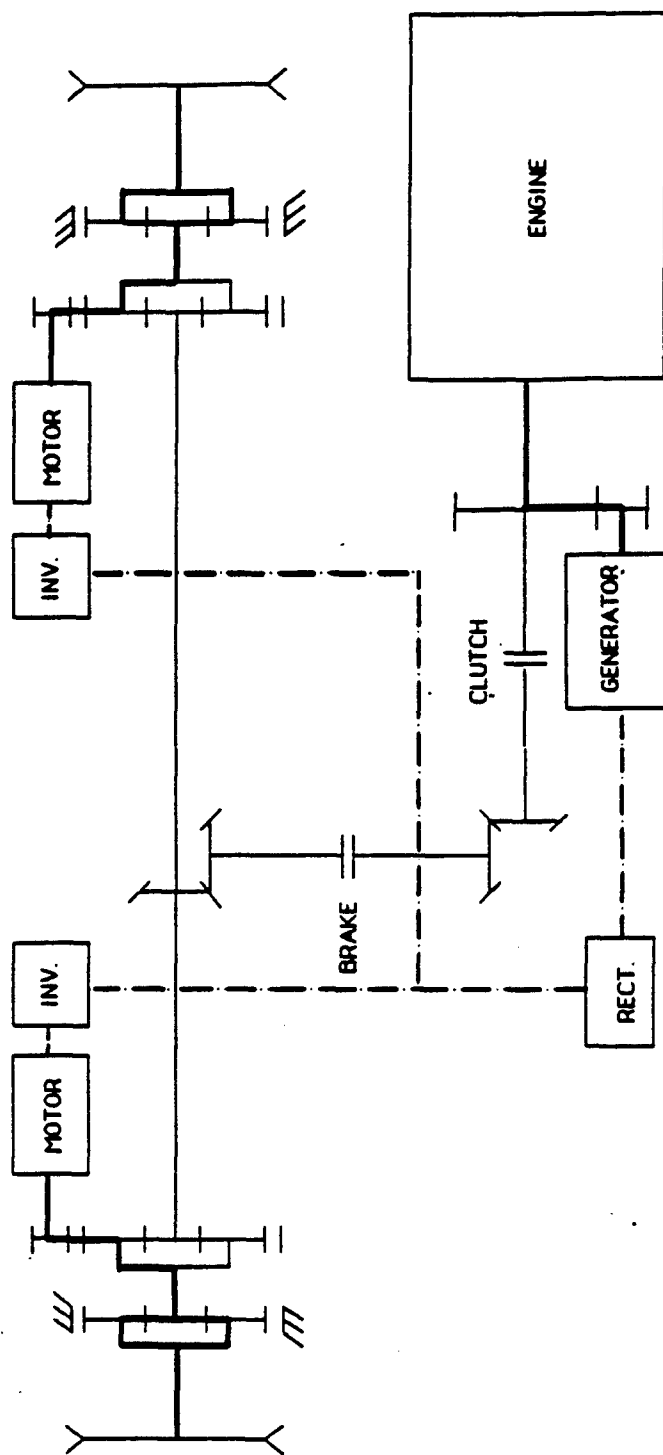


Figure 5.4-48. Power Flow Schematic High Gear Power Path,
19.5 and 40.0 Ton Garrett Concepts

UNIQUE MOBILITY 19.5 TON
POWER FLOW SCHEMATIC



MECHANICAL POWER ———
ELECTRICAL POWER - - -

Figure 5.4-49. Power Flow Schematic Electrical Path ONLY
(Low Speed), 19.5 Ton Unique Mobility Concept

UNIQUE MOBILITY 19.5 TON
POWER FLOW SCHEMATIC

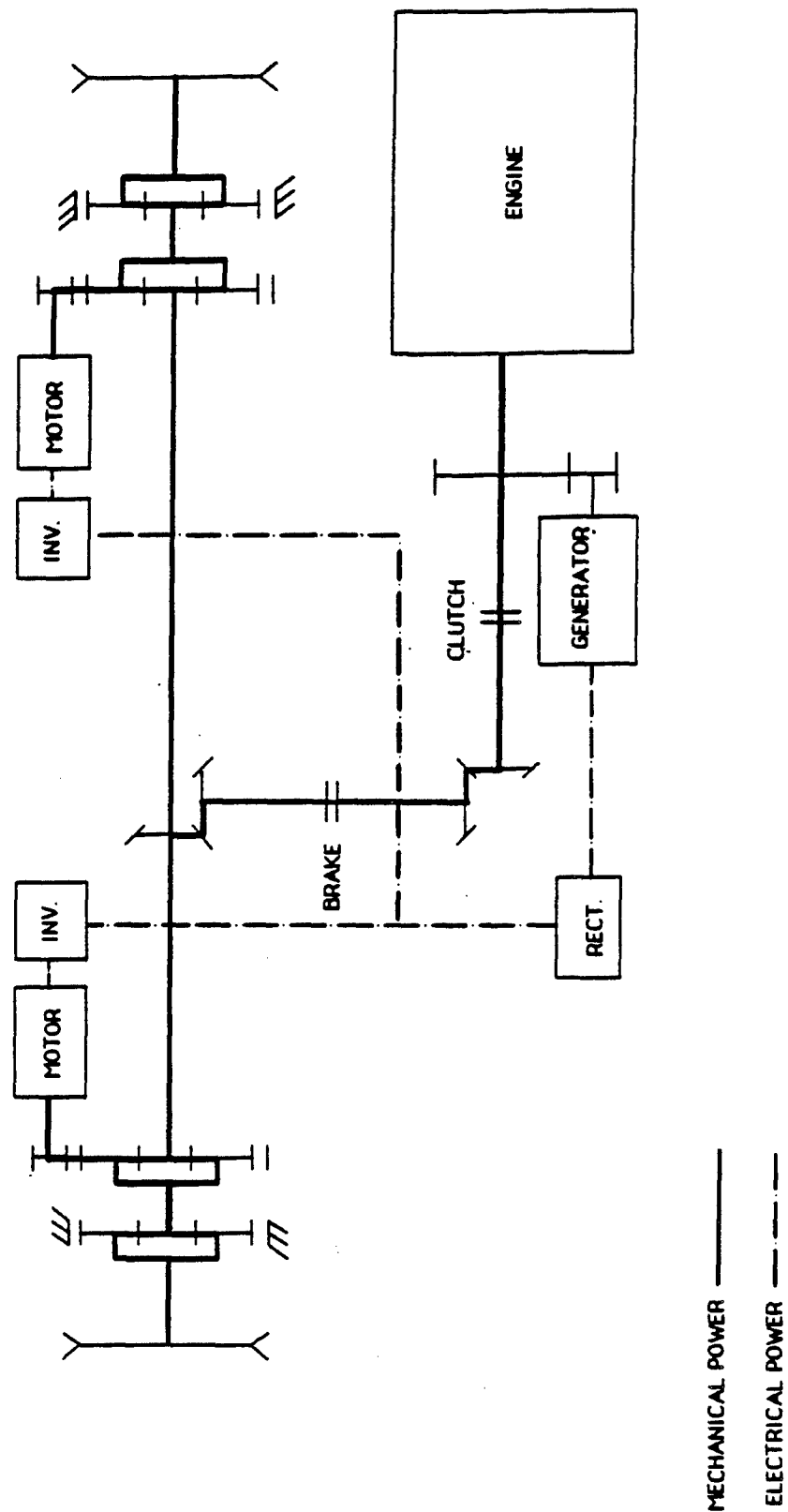


Figure 5.4-50. Power Flow Schematic Electro-Mechanical
Path (High Speed), 19.5 Ton Unique Mobility Concept

Figures 5.4-51 and 5.4-52 show the power flow schematics for the 40 ton Unique Mobility concept in electric and electric-mechanical modes. This drive train concept performs exactly as described for the lighter vehicle class. However, it was desirable to use two motors at each final drive sprocket to avoid high gear tooth loads.

5.4.11.6 Simulation of Electric Drive Dynamic Performance

We demonstrate the control and scheduling algorithms discussed in sections 5.4.10, 5.4.10.1, and 5.4.10.2 by presenting typical results from a simulation computer program that integrates the mechanical equations of motion for the prime mover/alternator, traction motors/vehicle systems. These equations of motion are given below:

$$J \frac{dw_g}{dt} = T_{pm} - T_{gen} - T_{aux} \quad (A)$$

$$\text{and } M \frac{d}{dt} = F_{mout} + F_{min} - F_t \quad (B)$$

$$I \frac{d}{dt} = F_{mout} + F_{min} - F_s \quad (C)$$

where

J = equivalent moment of rotary inertia of the prime mover/alternator combination measured at the alternator shaft,

w_g = alternator shaft speed,

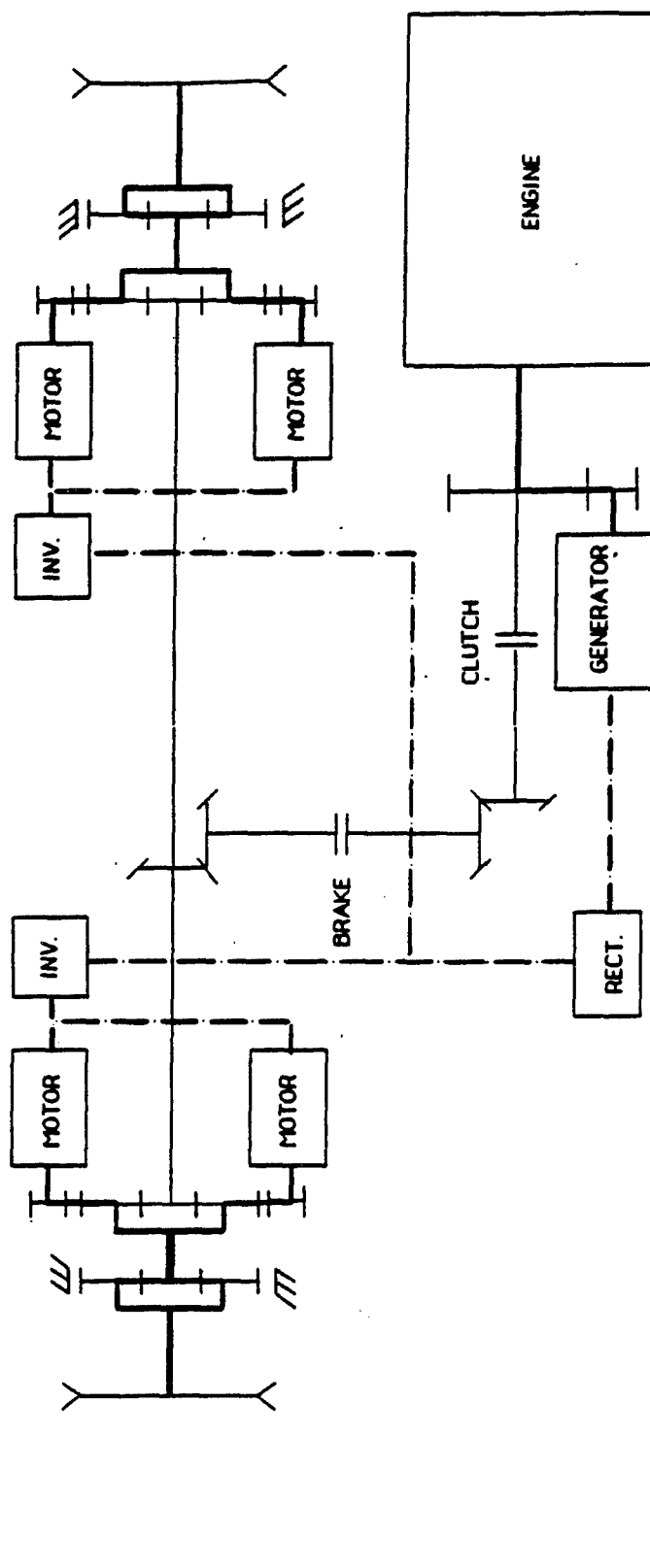
t = time

T_{pm} = prime mover drive torque at the alternator shaft,

T_{gen} = alternator air gap (i.e., load) torque,

T_{aux} = damping and auxiliary load torque measured at the alternator shaft,

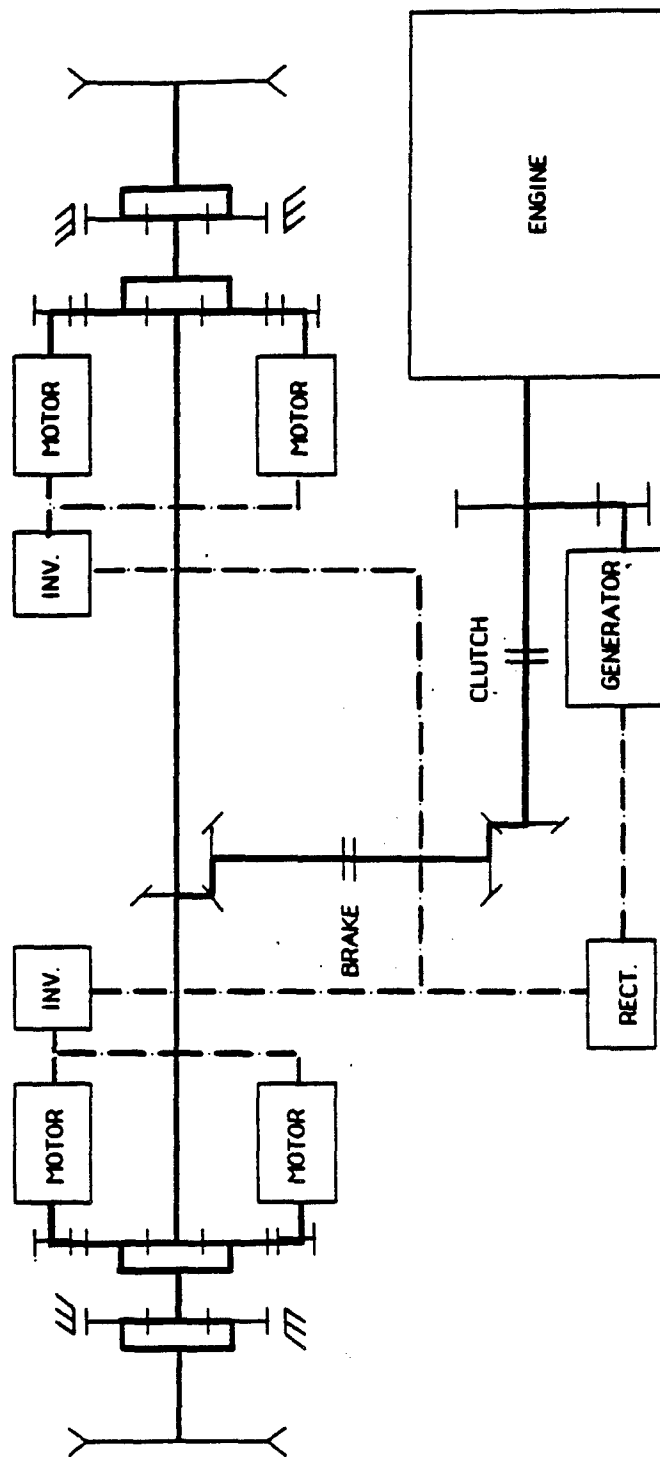
UNIQUE MOBILITY 40.0 TON
POWER FLOW SCHEMATIC



MECHANICAL POWER ———
ELECTRICAL POWER - - -

Figure 5.4-51. Power Flow Schematic Electro-Path
ONLY (Low Speed), 40.0 Ton Unique Mobility Concept

UNIQUE MOBILITY 40.0 TON
POWER FLOW SCHEMATIC



MECHANICAL POWER ———
ELECTRICAL POWER - - -

Figure 5.4-52. Power Flow Schematic Electro-Mechanical
Path (High Speed), 40.0 Ton Unique Mobility Concept

- M = equivalent total vehicle mass, including rotational inertia contributions from the traction motors and gear reduction sets.
- v = mean vehicle land speed (i.e., average of outside and inside track velocities),
- F_{mout} = traction force exerted by outside track,
- F_{min} = traction force exerted by inside track,
- F_t = traction retarding force due to rolling resistance, grade resistance, air resistance, etc. (assumed equal to 100 lbs/ton for level hard surface),
- I = equivalent turbine moment of inertia for the vehicle about a central vertical axis (assumed equal to 33000 slug ft² for the 19.5 ton vehicle),
- Δv = difference between outside and inside track velocities,
- F_s = slewing resistance force (see ATAC Technical Report No. 10969).

The coupling between the prime mover/alternator system and the traction motor/vehicle system is the electric drive train. Simple schematics for the DC representation of the electric drive trains of the three best concepts chosen in this study are given in figures 5.4-32 and 5.4-33 in section 5.4.10.1 of this report. From these schematics we see that the coupling terms T_{gen} , F_{mout} , and F_{min} can be determined at any time by the solution of a very simple DC electrical circuit. Note that the track force terms F_{mout} and F_{min} are directly proportional to their respective traction motor output torque. The proportionality factors are products of the respective speed reduction ratios (motor shaft speed to sprocket speed) and the inverse of the track drive sprocket radius. For the case of simple straight ahead motion equations A and B, the equations of the electric drive equivalent circuit and the control equations for the prime mover input fuel rate, the alternator controlled converter firing angle and the traction motor controlled converter firing

angles* must all be solved simultaneously in order to truly simulate vehicle motion. For the case of motion with both translational and rotational (steering) components equation C must be added to the solution set.

As a specific example consider the 19.5 ton Garret concept. We repeat the schematic for this concept in figure 5.4-53, but in this case we supply the actual values for the circuit elements. However, these values are in a normalized system commonly employed in electric power problems wherein all element values are dimensionless. This dimensionless system is referred to as the per unit system. To obtain the actual circuit element value each normalized element value must be multiplied by its respective normalizing constant or base value. If we choose the base values of the circuit variables, (power, torque, machine speed, current, voltage, etc.) to be near or equal to their respective rated values then near rated operation all circuit variables will be near unity. Also from these base circuit variables we can derive base values for the circuit elements. For example, a base resistance is defined as:

$$R_{base} = V_{base} / I_{base} = P_{base} / I_{base}^3$$

Where R_{base} , I_{base} , and P_{base} are the network voltage base, the network current base and the network power base respectively. For the Garrett 19.5 ton vehicle we choose.

$P_{base} = 500 \text{ HP} = \text{rated prime mover power,}$

$\omega_{gbase} = 18000 \text{ RPM} = \text{rated alternator speed}$

$\omega_{mbase} = 4600 \text{ RPM} = \text{lowest speed at which rated motor power can be attained,}$

$V_{base} = 840 = \text{rated input voltage to the series connected motor PCU's.}$

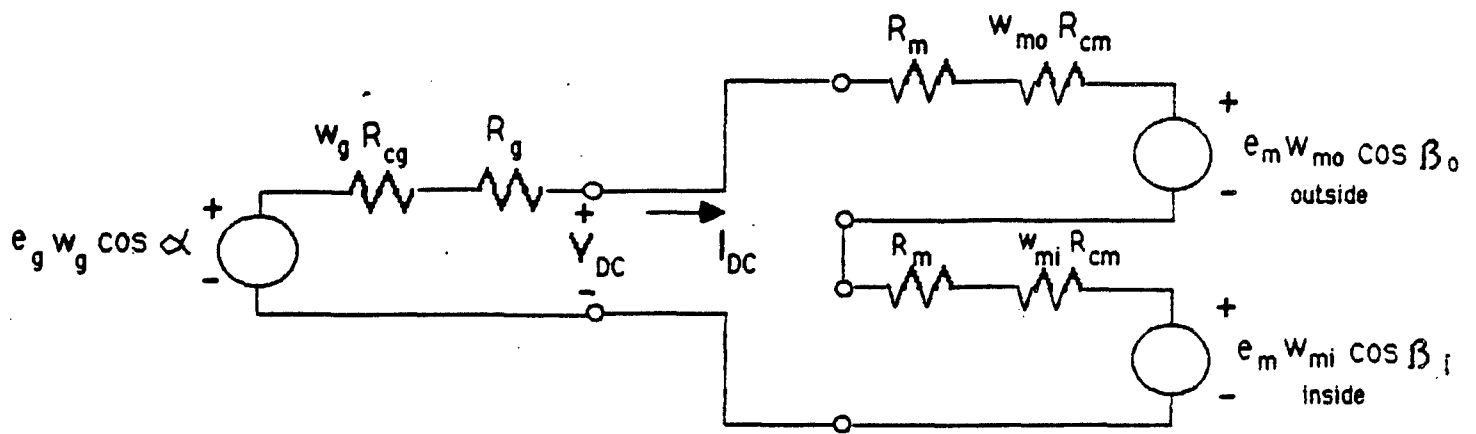


Figure 5.4-53. An Equivalent Electrical DC Circuit of the
Garrett 19.5 Ton Concept Electric Drive Train

This

$$I_{base} = P_{base}/V_{base} = 444 \text{ amps}$$

$$R_{base} = V_{base}/I_{base} = 1.89$$

the true beauty of the per unit system is that once you are "in" there is no longer any need for conversion constants. For example shaft torque in per unit (abbreviated PU) is simply the ratio of the shaft power in PU to shaft speed in PU. One does not need to worry about the correct constants needed to convert from watts and RPM's to foot-pounds. Of course one must use the correct conversion constants to properly get into the PU system. Also in a per unit system, speeds that are related by a fixed ratio are equal in per unit if the base speeds are chosen to be in the same fixed ratio. An example of this simplification is the relationship between a traction motor shaft speed and its respective track land speed for a fixed gear ratio (such as first gear in a two speed reductions). If we choose

$$V_{base} = \frac{W_{mbase}}{GR} \times R_{spkt}$$

Where V_{base} is the track speed base speed, GR is an actual numeric fixed reduction ratio between the motor shaft speed and the track drive sprocket shaft speed (usually chosen to be first gear) and R_{spkt} is the actual drive radius of the sprocket, then as long as the system remains in first gear

$$W_{mout}(pu) = V_{out}(pu)$$

$$W_{min}(pu) = V_{in}(pu)$$

If the gear ratio is changed by a fixed step then the per unit speeds are no longer equal but are in direct proportion to this fixed step.

The rated efficiency of the 192HP Garrett traction motors is 93 percent at base speed, 4600 RPM. Thus in per unit the rated motor current is

$$I_{or} = \frac{192HP}{\eta_r (.5V_{or}) (500HP)Pu}$$

Note that we have neglected both alternator and motor PCU loss in the circuit of figure 5.4-53. The steady-state results given in tables 5.4-26 to 5.4-35 of section 5.4.8 do, however, account for PCU loss and in fact employ a more sophisticated (i.e., more accurate) PM machine model as well.

Since $V_{Or} = 1.0$ pu, we find $I_{Or} = 0.826$ pu. The drive train loss for this simple model is then given by;

$$P_{loss} = (R_{sg} + 2 R_{sm}) I_o^2 \text{ pu}$$

Recall that the overlap resistance R_{ug} and R_{um} do not contribute to loss, and the required internal alternator voltage at any operating is

$$E_g W_g \cos \alpha = (R_{sg} + W_g R_{ug} + 2 R_{sm} + (W_{mout} + W_{min}) R_{um}) I_o + E_m (W_{mout} \cos \beta_{out} + W_{min} \cos \beta_{in}) \text{ pu}$$

At rated output for straight ahead motion at the vehicle base speed $W_g = W_{gbase}$, $I_o = I_{Or}$ and $W_{mout} = W_{min} = 1.0$ pu, we obtain for $\cos \beta_{out} =$
 $\cos \beta_{in} = \cos \beta_{min} = 0.866$,

$$P_{loss} = 0.107 \text{ pu}$$

and

$$e_g \cos \alpha = 1.143 \text{ pu}$$

Thus the "electrical" efficiency of the total electric drive train is 87.8 percent and the required firing angle for the alternator controlled converter is $\arccos(.953) = 17.7^\circ$.

The above analysis is an example of steady-state analysis of the complete electric drive train. We assume that in relation to vehicle motion the "electric" variables are always in the steady-state. That is, the electrical transients are so much faster than the vehicle mechanical transients that we need only solve the mechanical differential equations, equations A, B, and C.

There is no need to solve electrical differential equations since the actual electrical transients die out too fast. The electrical network is then in effect in the "steady-state" at all times in the time frame of the mechanical transients. The electric drive train computer simulation uses this simplifying approximation in its solution algorithm. The remaining system variables and constants needed for simulation of the Garrett 19.5 ton concept are given in table 5.4-51.

As examples of simulation results we present two case studies. The first is straight ahead vehicle acceleration from standstill to a desired speed of 25 mph. These results as a function of time are given in figure 5.4-54 and 5.4-55. In figure 5.4-54 the vehicle mean speed in mph, the engine/alternator speed in per unit and the drive train DC current in per unit are plotted together versus time. In figure 5.4-55 vehicle mean speed in mph (repeated from figure 5.4-54), the alternator PCU Cos ϕ , the traction motors PCU Cos β , and the prime mover fuel rate in lb/hr are plotted together versus time. The vehicle two speed gear boxes are locked in high gear for this run. The simulation control functions include an engine overspeed governor model that prevents engine overspeed if the electrical load on the alternator is not sufficient to completely load the prime mover during hard acceleration at traction motor speeds below the rated power speeds. This governor action can be seen in figure 5.4-55 for vehicle speeds below 15 mph, that is the vehicle speed at the base speed of the traction motors when the gear boxes are in high gear. Of particular note in figure 5.4-55 is the transition from hard acceleration, during which time the prime mover fuel rate is at or near its maximum (or governed maximum) value, for steady-state operation. This transition occurs in the 10 to 16 second time frame. The transition takes place in two distinct steps: first, at time = 11.4 seconds the mean speed is within 2.5 mph of the desired speed and the hard acceleration bias on the fuel rate control loop is removed. At approximately 13.4 seconds the traction motor Cos β control loop comes out of saturation and the optimum fuel consumption control is within its linear region of operation. The engine/alternator speed, the DC link current, and the engine fuel rate quickly approach their respective optimum values and the vehicle speed is maintained at near the desired value. Since we use simple proportional control, that is

Table 5.4-51. GARRET 19.5 TON DRIVE TRAIN CONCEPT,
SYSTEM VARIABLES AND CONSTANTS

VT-903 Prime Mover

$$T_{pm} - T_o (FR-FR_o)^{m_o} \text{ (pu)}$$

Where

$$T_o = 0.972 - 0.647 \times W_g$$

$$FR = (\text{Fuel rate in lb/hr})/50 \text{ lb/hr}$$

$$FR_o = -0.21 + 0.751 \times W_g$$

$$M_o = 0.221 + 0.679 W_g$$

$$\text{minimum FR} = 0.11 \text{ (pu)}$$

Prime Mover/Alternator

$$J = 1.17 \text{ (seconds)*}$$

$$T_{aux} = 0.16 \times W_g \text{ (pu) (an assumed pure damping load)}$$

$$\text{transfer case efficiently} = 0.98$$

Traction Motors/Vehicle

$$M = 0.274 \text{ (seconds)*}$$

$$F_t = 0.0523 \text{ (pu) (hard, level surface)}$$

$$\text{total speed reduction gearing efficiency (including final drive)} = 0.96$$

$$I = 0.3 \text{ (seconds)*}$$

$$F_s = \text{see ATAC Technical Report No. 10969, put in per unit by normalizing to a force base of 18,700 lb.}$$

*In our per unit system all variables are dimensionless except time, therefore all inertia values will have units of time. In our case, time is measured in seconds.

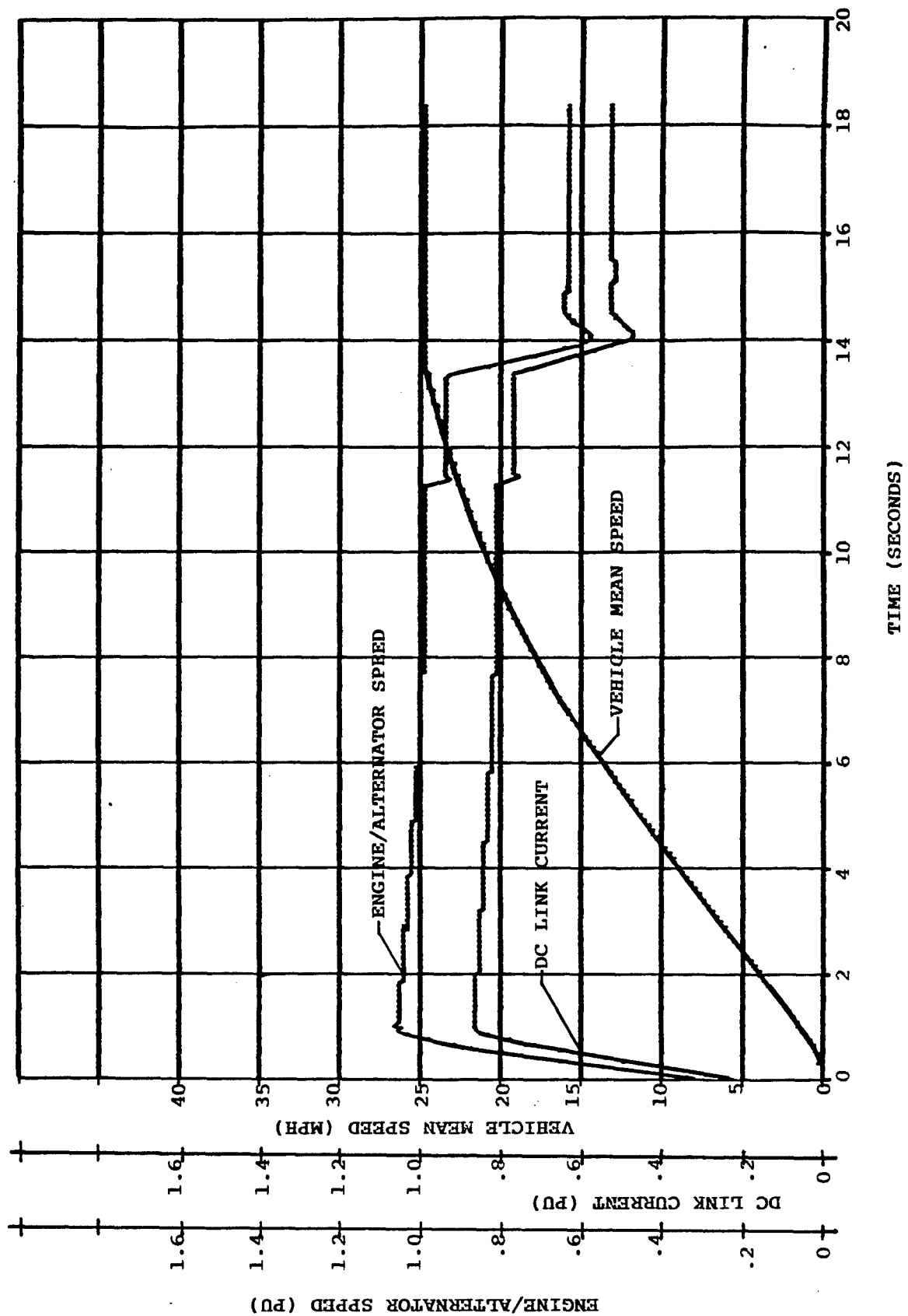


Figure 5.4-54. Simulation of Dash to 25 MPH for
Garrett Concept 19.5 Ton Vehicle

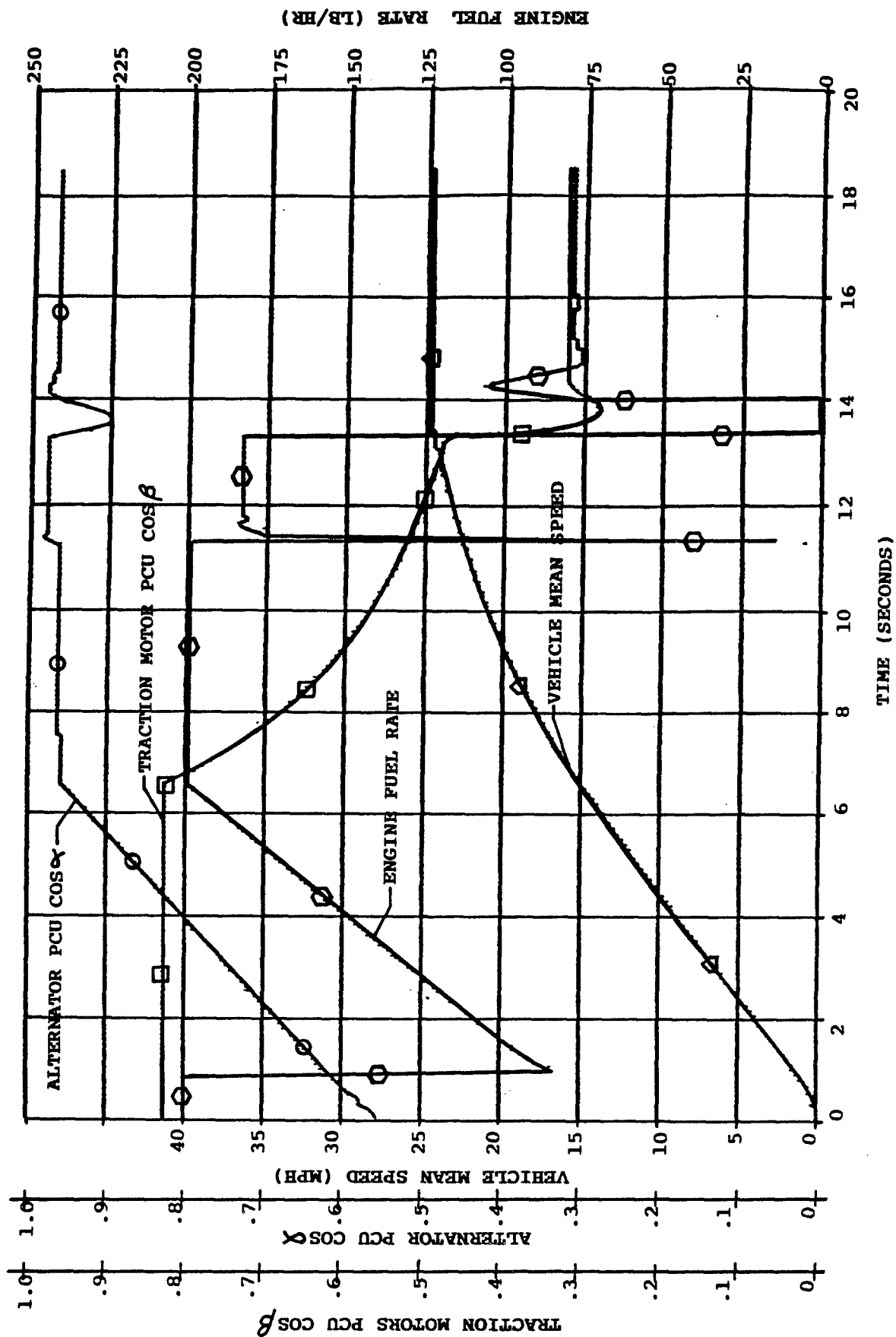


Figure 5.4-55. Simulation of Dash to 25 MPH for
Garrett Concept 19.5 Ton Vehicle

$$\text{Cos } \beta = K_{\beta} (V_{\text{demand}} - v)$$

where K_{β} is the loop gain constant, there will be a steady-state error proportional to $1/K_{\beta}$.

The second simulation example we present is the computed results for a near skid-out turn at an initial vehicle speed of 27.5 mph. The vehicle enters the turn region at steady-state and at optimum fuel consumption control. At a given position a step command is given for a desired turning radius of 75 ft. After a period of transition a state of nearly steady-state turn operation is achieved. The turn command is then removed and the vehicle resumed straight ahead operation. The results for this sequence of events for the Garrett 19.5 ton vehicle are shown in figure 5.4-56. Plotted in figure 5.4-56, as a function of vehicle translational position (time integral of mean speed) are the vehicle mean speed in mph, the DC link current in per unit, the engine/alternator speed in per unit, the achieved radius of turn in feet, and the track differential velocity in mph.

During a hard turn such as this, the fuel rate and DC link current control functions receive a bias signal to increase fuel consumption and overload the DC link current. The traction motors, particularly the outside track motor (see tables 5.4-26 to 5.4-35), are also in an overload state.

This turn could not be sustained indefinitely in an actual vehicle. Note that the DC link current rises to peak of near 1.5 pu during the turn initiation (recall that the rated link current for this vehicle is 0.826 pu). The turn signal is initiated at position = 10 ft and removed at position = 150 ft. Note that immediately after the turn command removal there is a temporary engine/alternator speed overshoot due to the removal of the overload state. The slight vehicle mean speed droop which occurs during the turn period is due to the marginal capability of this drive train to maintain this worst case skid out turn at the required speed, 27.5 mph.

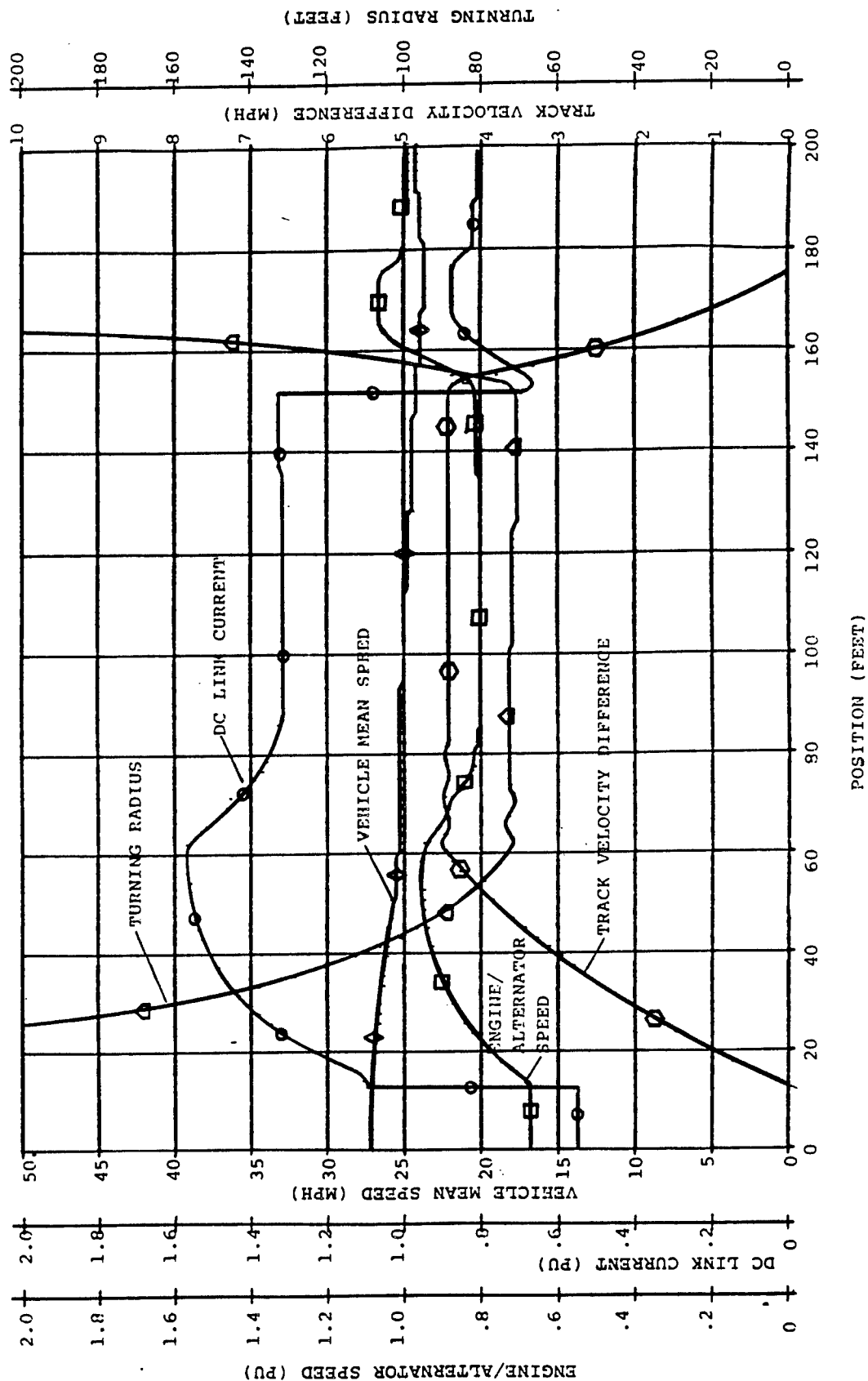


Figure 5.4-56. Simulation of Near Skid-Out Turn at 27.5 MPH for Garrett Concept 19.5 Ton Vehicle

The two examples of electric drive train simulation results that have been presented here have been included to show the dynamics of the control and scheduling laws for the drive train components. The drive train simulation program itself is still in the development stage and not suitable for inclusion in this report.

5.4.12 Brake System Description

The brake system for the three best electric drive concepts provides the braking function by a combination of mechanical friction and electric regenerative braking under microprocessor control. The friction brakes are hydraulically actuated wet disc brakes located in the gearbox at each drive sprocket immediately before the final drive. The electric braking is accomplished by coupling energy from the traction motor (acting in generator mode) back to the engine and to a resistance grid. The electric and friction brake systems are separate systems that in combination are designed to provide the vehicle with an average deceleration rate of 16.4 FT/SEC^2 on a level hard surface road for:

- A single stop from 45 mph in 4.0 seconds and
- 25 stops from 37.5 mph in 4.0 seconds at 3 minute intervals

Either of these brake systems acting separately can provide reduce braking capability in case of an emergency. Figure 5.4-57 gives the braking capability of the electric and friction brake systems acting separately and in combination for the vehicle initially at 45 miles per hour. The friction brakes are designed to hold the vehicle on a 60 percent grade with the engine off.

The friction brakes are multiple plate assemblies consisting of bronze friction plates splined to the driven shaft and steel reaction plates splined to the stationary gearbox housing and a hydraulic piston that forces the plates in the pack together to produce braking. The friction brake system for the 19.5 ton vehicle uses 13 plates (7 reaction and 6 friction plates) at each drive sprocket and the 40.0 ton vehicle requires 19 plates (10 reaction and 9 friction plates) at each sprocket. The area of one plate face is approxi-

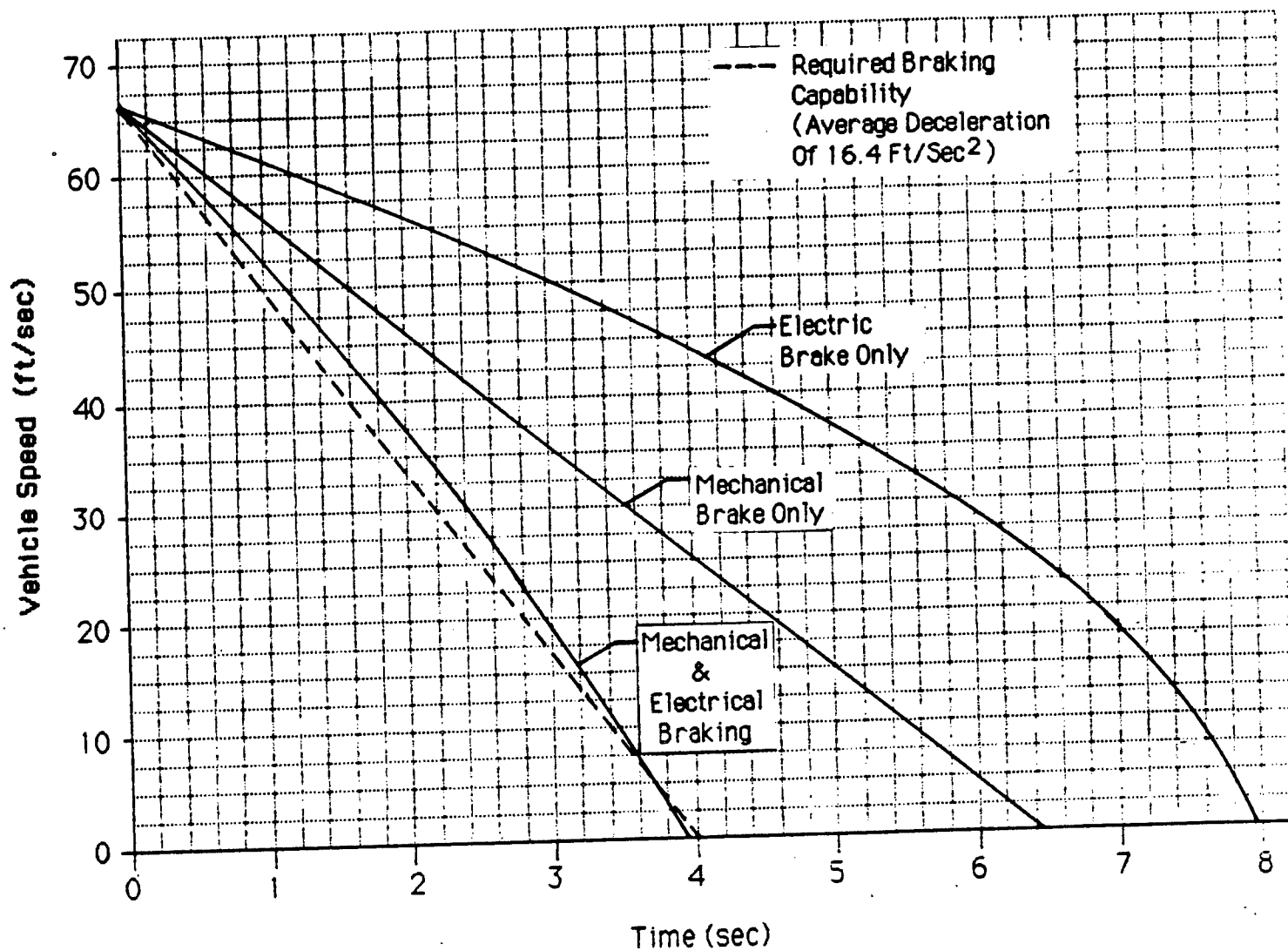


Figure 5.4-57. Brake System Performance

mately 45 square inches for the 19.5 ton vehicle and 50 square inches for the 40.0 ton vehicle. A dynamic friction coefficient of 0.12 was assumed for bronze on steel. The maximum energy absorbed by the friction brakes during a stop from 45 mph in 4.0 seconds is 1,650,000 FT-LB at an average rate of 750 HP for the 19.5 ton vehicle and 3,120,000 Ft-LB at an average rate of 1420 horsepower for the 40.0 ton vehicle. The resulting energy and power densities of the plates are 1535 FT-LB/IN² and 0.67 HP/IN² for the 19.5 ton vehicle and 1750 Ft-LB/IN² and 0.78 HP/IN² for the 40.0 ton vehicle.

The electric brake system is activated by reversing the traction motor stator field and operating the motors in generator mode. The load in this case is the resistance provided by the engine and a resistance grid. The braking horsepower of the VTA-903T engine is approximately 125 HP at 2600 rpm. If the cooling fan power and the inefficiency of the electric drive system in regeneration mode are considered then the total engine braking power for the 19.5 ton vehicle is 230 horsepower. The total engine braking power for the 40.0 ton vehicle is 290 horsepower when the fan power and efficiency are included. The AD1000 engine along is assumed to provide 125 horsepower in braking.

The additional braking load required by the electric brake system is provided by electric resistance grids that are located in the cooling system air exhaust downstream from the heat exchanger. The exhaust air provides adequate cooling of the resistance grids. The resistance grids required for the electric brake system of the 19.5 ton vehicle weighs 70 pounds and occupies 1.5 cubic feet. The resistance grid required for the 40.0 ton vehicle weighs 150 pounds and occupies a volume of 3.3 cubic feet. The electric braking system can provide dynamic braking that will allow continuous descent on a 15 percent grade at nearly any vehicle speed without using the friction brake system.

5.5 COMPARISON OF BEST ELECTRIC TRANSMISSION CONCEPTS WITH MECHANICAL TRANSMISSIONS

A comparison of the best three electric drive concepts with selected mechanical transmissions is presented in this section for 19.5 and 40.0 ton vehicle applications. The Government selected the Detroit Diesel Allison X300-4A and ATT1064 transmissions for the comparison. The Government also

provided physical and performance data of these mechanical transmissions for the comparison.

The weight, volume, efficiency, and performance of the three best electric drive concepts and the selected mechanical transmissions are compared in the following subsections.

5.5.1 Physical Characteristics

This section presents and compares the weight and volume characteristics of the three best electric drive train concepts with the selected mechanical transmission for the 19.5 ton and 40 ton vehicle weight classes. The weight and volume data presented for the comparison of electric and mechanical transmissions are for bare units - final drives, cooling system, and miscellaneous installation hardware are not included. Table 5.5-1 shows the physical characteristics of the electric transmission concepts and the X300-4A transmission for the 19.5 ton vehicle class.

TABLE 5.5-1. COMPARISON OF ELECTRIC TRANSMISSION CONCEPTS
AND MECHANICAL TRANSMISSION FOR THE 19.5 TON VEHICLE

	<u>WEIGHT (LBS)</u>	<u>VOLUME (FT³)</u>
<u>Electric Transmissions</u>		
Unique Mobility	1240	9.5
Garrett	1440	9.3
ACEC	1960	10.0
<u>Mechanical Transmission</u>		
DDA X300-4A	2000	20.0

Comparison of these physical data to X-300 mechanical transmission clearly shows the volume and weight reduction possibilities each electric drivetrain has to offer. Table 5.5-2 shows the physical characteristics of the transmissions for the 40 ton vehicle.

TABLE 5.5-2. COMPARISON OF ELECTRIC TRANSMISSION CONCEPTS
AND MECHANICAL TRANSMISSION FOR THE 40.0 TON VEHICLE

	WEIGHT <u>(LBS)</u>	VOLUME <u>(FT³)</u>
<u>Electric Transmissions</u>		
Unique Mobility	2000	14.7
Garrett	2300	12.5
<u>Mechanical Transmission</u>		
DDA ATT 1064	2600	17.0

These data show the volume and weight reduction advantages that an electric transmission could have relative to a comparable mechanical transmission - the ATT1064.

Significant volume reductions are shown for the electric transmission concepts for both the 19.5 and 40.0 ton vehicle applications. However, the volume improvement relative to the mechanical transmission is less for the 40 ton vehicle application because the ATT1064 transmission is a volume efficient, six speed advanced design while the X300 transmission is a current production unit.

In addition to the volume improvements, the modular nature of the electric transmission concepts afford improved space utilization and design alternatives not allowed by mechanical transmissions. For example, in a vehicle system where interior hull volume is critical, approximately 50 percent of the electric transmission volume can be located outside the hull interior by nesting gearboxes and traction motors in the drive sprockets and locating electronic power conditioning units in the vehicle sponsons.

5.5.2 Transmission Efficiency

Efficiency over the vehicle speed range was determined for the best electric transmission concepts and the selected mechanical transmissions for the 19.5 ton and 40.0 ton vehicle applications. The efficiency values are for linear propulsion mode and do not include final drive losses. The efficiency comparison of the best electric transmission concepts and of the mechanical transmissions is presented in figure 5.5-1 for the 19.5 ton vehicle application and figure 5.5-2 for the 40.0 ton vehicle application.

The average efficiency over the vehicle speed range of 5 to 45 miles per hour of the best electric transmission concepts and of the mechanical transmission for the 19.5 and 40.0 ton vehicle applications are given as follows:

19.5 TON VEHICLE APPLICATION

ACEC Concept I-5	83%
Garrett Concept I-10	78%
Unique Mobility Concept IV-2	87%
X-300 Mechanical Transmission	83%

40.0 TON VEHICLE APPLICATION

Garrett Concept I-10	79%
Unique Mobility Concept IV-2	88%
ATT1064 Mechanical Transmission	86%

Generally the average efficiency of the ACEC and Unique Mobility concepts are similar to the average efficiencies of the mechanical transmissions. The Garrett concept has lower average efficiency relative to the mechanical transmissions. Generally the electric drive concepts are more efficient at the 0.70 tractive effort point than the mechanical transmissions. This results in lower heat rejection at this 0.70 tractive effort condition for the electric transmission concepts.

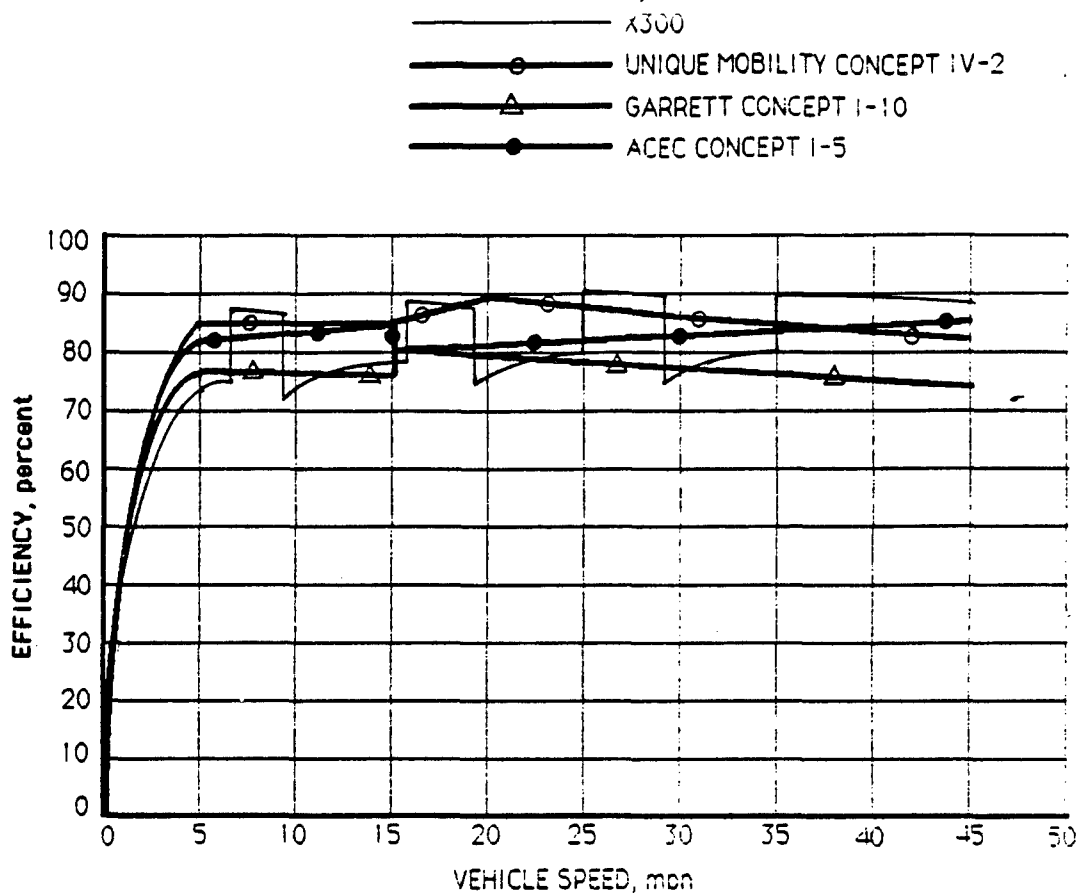


Figure 5.5-1. Comparison of Efficiency for Electric and Mechanical Transmissions of the 19.5 Ton vehicle Category

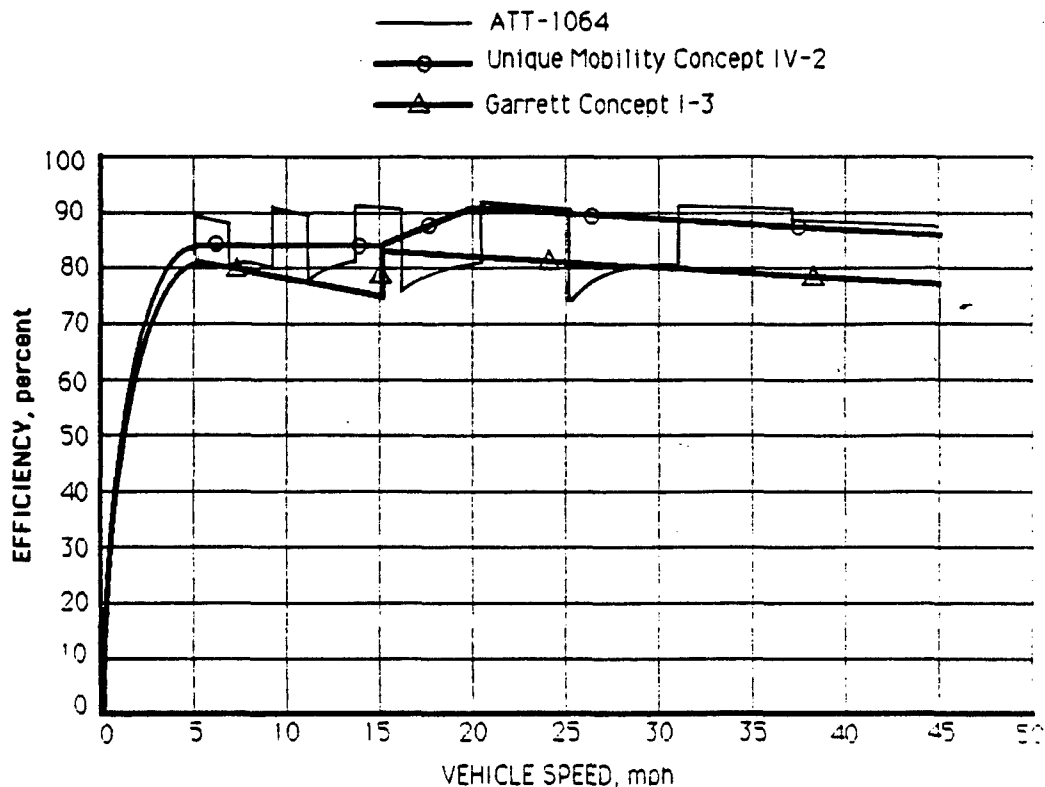


Figure 5.5-2. Comparison of Efficiency for Electric and Mechanical Transmissions of the 40.0 Ton vehicle Category

5.5.3 Vehicle Performance

The performance of the 19.5 and 40.0 ton vehicles with the best electric drive concepts was presented in section 5.4.11. The performance of the 19.5 ton and 40.0 ton baseline vehicles with the selected mechanical transmissions are presented in this section and compared with the performance of the baseline vehicles with electric transmissions.

The tractive effort requirements for the 19.5 and 40.0 ton baseline vehicles and the tractive effort produced by the application of the X300-4A and ATT1064 transmissions to these vehicles are shown in figures 5.5-3 and 5.5-4. The X300-4A transmission application to the 19.5 ton vehicle provides tractive effort that is generally 12 percent below the required tractive effort in the 5 to 30 mile per hour vehicle speed range. The tractive effort data presented for the X300-4A transmission is based on torque converter operation in all four gears. The ATT1064 transmission application provides tractive effort that averages 13 percent below the requirements for the 40 ton vehicle in the 5 to 10 mile per hour speed range. Above 10 miles per hour vehicle speed the tractive effort rapidly approaches the required values. The tractive effort data presented for the ATT1064 transmission application is based on torque converter operation in the first five gears of this six forward gear design. The tractive effort data of figures 5.5-3 and 5.5-4 are based on a final drive ratio of 3.80:1, a torque converter stall torque ratio of 3.02:1 and 427 maximum net input horsepower for the X300-4A transmission and on a final drive ratio of 4.09:1, a torque converter stall torque ratio of 1.92:1, and 855 maximum net input horsepower for the ATT1064 transmission applications.

The tractive effort data of figures 5.5-3 and 5.5-4 was used to develop acceleration and speed on grade values for the 19.5 and 40.0 ton vehicles with mechanical transmissions. Table 5.5-3 gives a comparison of the maximum speed attainable on grades of 10, 20, and 60 percent for the best electric transmission concepts and the selected hydrokinetic transmissions. A comparison of the acceleration times (from zero to 20 miles per hour) for the electric and hydrokinetic transmissions is given in table 5.5-4. The electric transmissions in most cases meet or exceed the speed on grade achievable with the hydrokinetic transmissions.

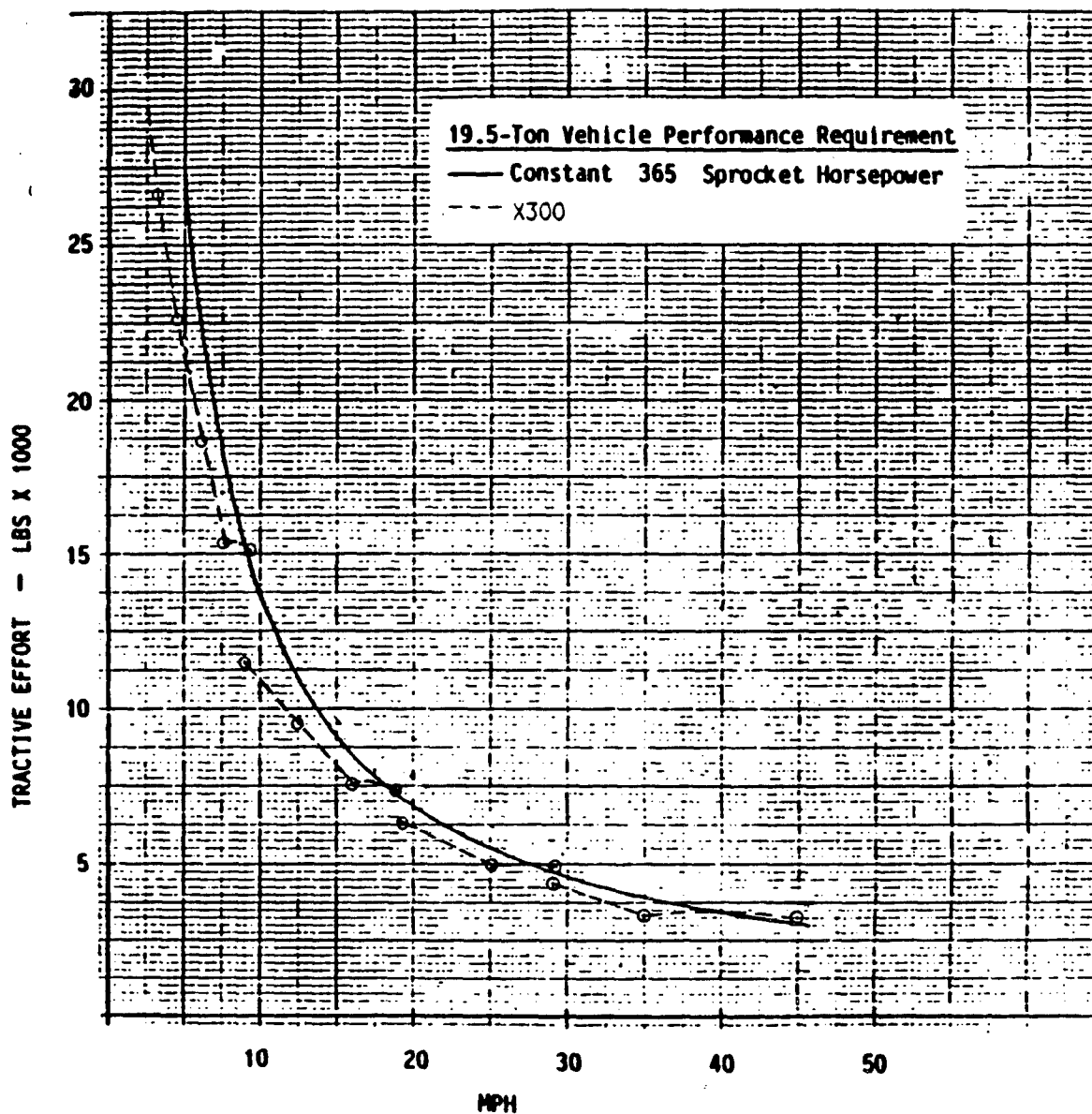


Figure 5.5-3. Tractive Effort for X300-4A Transmission, 19.5 Ton Vehicle

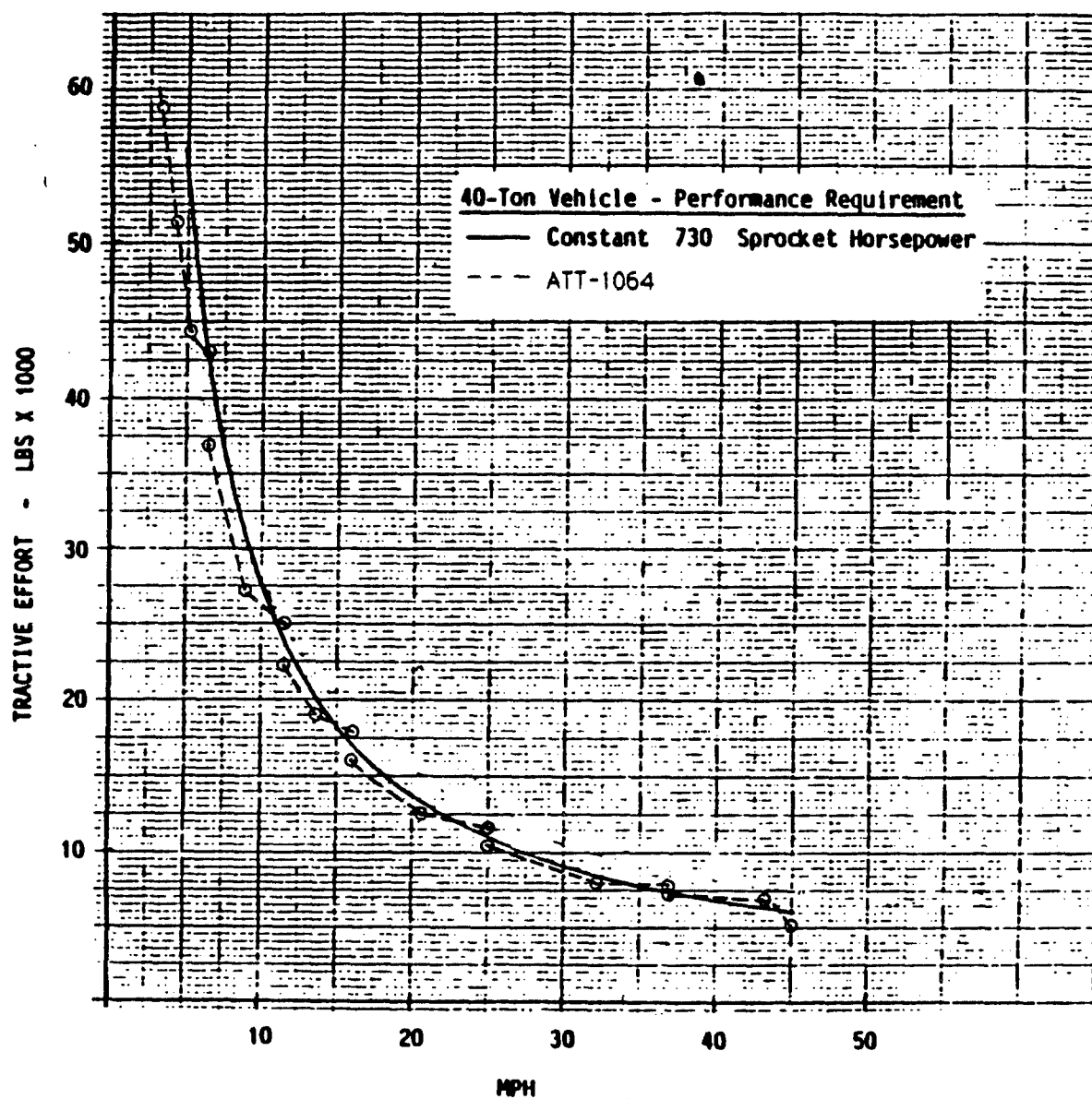


Figure 5.5-4. Tractive Effort for ATT1064 Transmission, 40.0 Ton Vehicle

TABLE 5.5-3 COMPARISON OF MAXIMUM SPEED ON GRADE FOR ELECTRIC
DRIVE AND MECHANICAL TRANSMISSION APPLICATIONS

<u>Vehicle Category</u>	<u>10% Grade</u>	<u>Maximum Speed MPH</u>	
		<u>20% Grade</u>	<u>60% Grade</u>
<u>19.5 Ton Vehicle</u>			
ACEC Concept I-5	22.0	13.5	5.5
Garrett Concept I-10	21.0	12.5	5.4
Unique Mobility Concept IV-2	24.0	15.0	5.6
X300-4A	21.0	12.5	4.8
<u>40.0 Ton Vehicle</u>			
Garrett Concept I-3	21.5	12.5	5.5
Unique Mobility Concept IV-2	24.5	15.0	5.7
ATT1064	22.0	13.0	5.0

TABLE 5.5-4. COMPARISON OF ACCELERATION TIME FOR VEHICLES
WITH ELECTRIC AND MECHANICAL TRANSMISSIONS

<u>Vehicle Category/Transmission</u>	<u>Acceleration Time (Sec)</u>
	From Zero to 20 MPH
<u>19.5 Ton Vehicle</u>	
ACEC Concept I-5	4.5
Garrett Concept I-10	5.1
Unique Mobility Concept IV-2	4.8
DDA X300-4A	7.5
<u>40.0 Ton Vehicle</u>	
Garrett Concept I-3	5.0
Unique Mobility Concept IV-2	4.4
DDA ATT1064	6.1

The Unique Mobility electric transmission concept gives the highest speed on grades in both vehicle weight categories and shows an improvement of 7 to 15 percent over the nearest competitor. The time values of table 5.5-4, for acceleration from zero to 20 miles per hour, show significant improvement for the electric transmissions relative to the hydrokinetic transmissions. The ACEC concept transmission gives a 40 percent reduction in the time to 20 miles per hour relative to the DDA X300 transmission in the 19.5 ton vehicle application and the unique mobility concept transmission achieves a 28 percent reduction in acceleration time relative to the DDA ATT1064 transmission in the 40.0 ton vehicle application. The acceleration time values of table 5.5-4 are generally given for vehicle start in second gear for hydrokinetic transmissions and vehicle start in high gear for electric transmissions that gives the lowest acceleration time values. Also the acceleration time values of table 5.5-4 were computed base on the assumption that engine power is instantaneously available to the transmission on demand.

5.6 ALTERNATE TECHNOLOGY/GROWTH POTENTIAL

The information generated in this study showed the potential an electric drivetrain has for the military vehicle. The best three electric drive concepts presented by this report are considered as near optimum transmission concepts. However, the integration of these best transmission concepts with the specified engines and other powerpack subsystems does not necessarily produce optimum powerpack concepts. The engines used in this study are limited to the Cummins VTA-903T and AD1000 engines - other engines and power sources should be investigated to define powerpack concepts with minimum installed weight and volume. The cooling systems developed during this study are conservative in design and should be further investigated with the objective of defining optimum cooling systems with minimum installed volume and fan power. Lastly, the powerpack layouts should be further examined for optimum component arrangements to achieve minimum installed volume and good maintenance features.

Other engines and primary power sources that should be considered in the search for optimum powerpacks which include transmission are now discussed.

5.6.1 Other Engine Candidates

Other engine candidates that should be considered for powering the electric drive concepts are minimum cooled turbo compounded versions that include the Cummins L10, the MTU 880 series, and the Deere Rotary Engines. The Cummins L10 is an in line six cylinder four cycle diesel engine while the MTU 880 Series comprise both in line and 90 degree Vee Type Diesel Engines. The Deere Rotary engine is a four cycle, stratified charge, spark ignition engine that was initially developed by Curtiss Wright. The above engine candidates have good growth potential, excellent fuel consumption rates over the engine speed range, and relatively low future development and unit production costs.

Also, the gas turbine engine should be investigated as a power source for hybrid electric propulsion systems. Use of high speed alternator design driven by the power turbine shaft of the gas turbine engine with little or no reduction gearing can potentially provide a volume efficient package. The gas turbine engine has excellent growth potential and projected life cycle cost. Major disadvantages of current turbine engine designs for military ground vehicles are high fuel consumption at idle and high development and unit production cost. The AVCO AGT800 and the Garrett GT601 (advanced versions) turbine engines are two candidates worthy of further investigation.

5.6.2 Free-Piston Engines

The Mothelec Corporation is currently developing a unique free-piston, combustion engine that offers a prospect for exceptionally good fuel economy, simplified power transmission, and improved power to weight ratio greater than currently achievable with conventional diesel or turbine engines.

This engine consists of a thermal cylinder in which two opposing pistons travel symmetrically during operation, two rectilinear alternators designed for electrically controlled pulsed excitation, and two liquid compression "springs" composed of a moving hydraulic cylinder fitted to each end of the machine. In operation, the expansion stroke of the pistons is caused by the burning action of the fuel, and the compression stroke that returns the

pistons is caused by the release of stored hydraulic energy in the cylinder. During the engine cycle, magnetic ring inductors, mounted on each piston shaft, activate the rectilinear alternators producing electrical energy. This energy can be easily regulated and transported to track drive motors for tractive effort.

Theoretical calculations and experimental evidence have shown this engine concept to be capable of producing the aforementioned benefits.

However, much development work remains to be done on this concept before a reliable, high performance, prototype engine alternator can be available, probably at least several more years. For the combat vehicle, the implication of this technology for fuel economy, design flexibility, and compatibility with electric transmissions, makes this approach highly desirable for future electric drivetrain concepts.

5.6.3 Fuel Cell as Powerpack

As part of the effort to generate electric drive propulsion concepts for an optimum system, fuel cells were examined as alternate power sources to replace the diesel or gas turbine engines in combat vehicles. A previous GDLS study showed that fuel cells could provide operational advantages over conventional engines when they are used to provide the vehicle tractive effort. The fuel cell has the ability to convert chemical energy of a fuel directly and electro-mechanically into useful electrical energy. Because this is done without a heat creation step, fuel cell operation efficiency tends to be greater than either the diesel or gas turbine engines that are governed by Carnot efficiency limitations. An improved efficiency means fuel can be consumed more completely with reduced waste heat production. Lowering the waste heat implies that the sizing of vehicle cooling system components could be downsized without penalty to heat transfer effectiveness of the system. Preliminary estimates of heat loss show the fuel cell yields a lower thermal signature compared to an equivalent diesel engine. This feature makes battlefield detection more difficult which is an obvious operational advantage for the combat vehicle.

A further advantage of a fuel cell is that it will eliminate the need for the transfer case and generator. These electric drive components, which were required by the diesel in all concepts generated during the study, become supefluous under the direct energy conversion scenario. Elimination of the generator and transfer case will result in significant improvement of the electric transmission efficiency that is on the order of 10 percent. Also the elimination of these components will not only improve system reliability, maintainability, and availability, but fewer mechanical parts suggest a quieter operation of the overall system. Coupling this feature with an electric transmission makes possible a vehicle propulsion system with lower audio signature.

As a result of this preliminary examination, the Lithium-Air fuel cell was seen to be particularly attractive as the power source in an electric drive application. This was due to the high power density, relatively low weight and space claim, and high operating efficiency of this fuel cell. Based on these and the system engineering advantages cited above, it is suggested that the Lithium-Air fuel cell could provide a more compatible match of power source to end use. Such development would also serve the military interest of preparing an advanced technology to satisfy the requirements of the future force mix and thereby preserve the competitive advantage.

5.7 PARAMETRIC STUDY OF ELECTRIC DRIVE COMPONENT TECHNOLOGIES

The parametric study is an additional effort awarded to General Dynamics Land Systems by the U.S. Army TACOM in September 1986 under MOD P00006 to the electric drive study contract. The parametric study encompasses the investigation of component technologies that are the foundation of compact, efficient, and lightweight electric drive systems for combat vehicles. These component technologies are discussed in section 5.7.1 and technology trends are established that indicate past, present, and future capability. The improvements accruing to the electric drive system and its subsystems from projected future advancements in component technologies are discussed in section 5.7.2.

5.7.1 Component Technology

The basic component technologies that are the foundation of electric drive machinery are discussed in this section and include the following:

- o Brushes
- o Insulation
- o Semiconductors
- o Magnetic Materials
- o Controls
- o Commutation
- o Cooling Techniques
- o Mechanical Structures (Frames, Bearing, Seals, Etc.)

Component technology trends are developed, where possible, based on past and present capability and projections of future capability. The growth or improvement in the component technologies can then be used to predict future improvements in electric drive machinery and systems. It is important to understand that typically electric machinery incorporates more than one technology and that there is not a one to one correlation between a specific technology improvement and the resulting improvement in electric machinery.

For example, consider two permanent magnet traction motors of the same rating and similar design except that one motor uses an improved permanent magnet material with an energy product that is 5 times greater than the other motor design. In this design example the use of permanent magnets with an energy product increase of 5 fold resulted in approximately a 50 percent reduction in motor weight based on actual hardware. It is clear that improvements in electric drive systems accruing from component technology advances are strongly dependent on specific design. Development of specific designs is beyond the scope of this study, however predictions of system improvements are made based on technology trends.

5.7.1.1 Brushes

Brushes are used in the very popular DC squirrel cage machine for commutation of current from one phase to the next. An investigation was made in the

application which showed brush development in the conventional DC machine is mature. These motors have been in use since the 30's and are still popular due to their low cost and simplicity. For these reasons there is no drive for improvement for this application of brushes.

Brush technology for continuous current collection is of primary interest in homopolar machinery. Studies during the late 1970's indicated that DC homopolar drive motors, which are equipped with brushes capable of high current densities, would compete favorably with hydro-mechanical transmissions, in tracked military vehicles, and permit increased arrangement flexibility. Performance evaluation of the tracked vehicle with homopolar drive systems showed that a higher horsepower could be delivered to the tracks at steady-state than with a hydro-mechanical drive for approximately 80 percent of the speed range of the vehicle. The weight and volume of the electric homopolar drives were competitive with the hydro-mechanical drive.

Brush materials for electric motor applications have been at a relative standstill since the early 1980's. No new material compositions, compounds, and/or elements have been introduced that have significantly advanced this technology. Brush materials for electric motors are still comprised of pure copper, and/or alloyed metals which range from copper, to varying portions of copper, silver, carbon, and graphite. These materials provide enhanced current collection capabilities. However, current density, speed, wear, and losses remain the highest priority criteria for system design.

During the seventies and early eighties, much experimentation was being done with liquid metal brushes. The liquid brushes could carry large current densities, however extensive systems had to be used to keep impurities from entering the liquid during the cooling process which made the concept rather impractical.

Research programs are now in progress to improve current densities in conventional brush materials. Improved methods of cooling brushes have produced positive results of up to 12,000 Amps per square inch.

One disadvantage of the homopolar machine is the fact that its brushes must be periodically replaced. Research is also being done to improve brush life by improving control of brush tension and temperature.

Brushes are also a limiting factor in rotor speed. If brush life can be significantly improved, then rotor speed can also be increased, thus reducing the size and weight of the total machine. Brush velocities of 200 m/sec are currently experimental. All of these improvements hold a promising future for brushes in large DC homopolar drive systems.

It is expected that if improvements in rotor speed can be realized by improving brushes it will significantly affect total size and weight of the DC homopolar machine. The improvements are expected to impact efficiency favorably.

There are several other areas of study in the brush technology which include testing of fiber brushes versus solid, brush lifting techniques to improve brush life and gas absorption. In addition, new methods of rotor cooling will make brush cooling more efficient.

5.7.1.2 Insulation

One of the most common and important questions in the application of rotating machines is "What maximum output may be obtained?" The answer of course depends on various factors. While providing an over load output, the machine must in general meet definite performance standards. A universal requirement is that the life of the machine shall not be unduly shortened by overheating.

The operating temperature of a rotating machine is closely associated with its life expectancy because deterioration of the electrical insulation is a function of both time and temperature, ultimately leading to a loss of mechanical durability and dielectric strength.

The evaluation of electrical insulating materials and complete systems of insulation (which includes widely different materials and techniques in combination) is to a large extent a functional one based on accelerated life tests.

Life tests generally attempt to simulate service conditions. They usually include the following elements:

- o Thermal shock resulting from heating to the test temperature
- o Sustained heating at that temperature
- o Thermal shock resulting from cooling to room temperature or below
- o Exposure to moisture
- o Dielectric testing to determine the condition of the insulation .

Electrical insulations for rotating machinery are rated in the three following categories:

- o Service Factor
- o Enclosure Type
- o Allowable Temperature Rise, °C

Electrical insulation materials encompass a wide variety of high quality specialty chemical materials and composites. These materials are used to produce insulating materials that include mica products, flexible insulation, wire enamels and films, varnishes, compounds, and adhesives.

Mica is the major material used in insulation systems by virtue of being both a positive dielectric barrier as well as corona resistant material. In addition, mica is unaffected by temperatures up to 600° and will withstand high compressive loading. In most motor/generator applications mica is used in the form of reconstituted mica paper (mica composite) to provide greater uniformity of properties for a more efficient utilization of space.

Mica composites provide high dielectric, voltage endurance, and thermal strength. Mica composites are also easily adaptable to mechanical applications and can be custom designed for tight tolerance requirements. Two mica composites of note are mica pressed composites and built-up mica composites.

Mica pressed composites consist of mica paper impregnated with synthetic resins and reinforced with varnish treated glass cloth or polyester film.

Built-up Mica composite is a flexible, partially cured material produced in sheets to form laminated structures in which reinforcing material provides the strength for handling and application.

Mica based material offers both near term and future benefits that are the most promising of all available R&D electrical insulation materials under review for rotating machinery applications.

Further development in the area of electrical insulation materials for electric machinery will depend largely on the advancements in the area of electrochemical engineering, and composite structures technology.

Advance research is being done on ceramic insulating materials for use in electric motors. Ceramic has superior qualities in the area of heat insulation and also electrical insulation. Therefore it has the potential to benefit the motor industry. Tests have been conducted successfully on motors using ceramic insulation consisting of running the motor at 500°C (DC squirrel cage type). One disadvantage of using ceramic insulation is that it is brittle and cannot withstand significant shock loads.

Advanced high temperature insulation systems will be important to rotating machinery in applications where limited or no cooling is required. Also, high temperature insulation will allow increased short time duty rating. However improved insulation system do not indicate any significant effect on the weight or volume of future rotating machinery designs.

5.7.1.3 Power Semiconductors

In power control and conditioning applications power semiconductor devices are used as on-off switching devices. Thus they are rated by their on-state current carrying capabilities and their off-state voltage blocking capabilities. The product of the device on-state current capability and the off-state voltage blocking capability is referred to as the device switching volt-amp (VA) capability and is an overall measure of the device usefulness as a power switch. Devices are also classified by the speed in which they can switch from the off-to the on-state, and vice-versa. In power conditioning applica-

tions for traction motor drives the switching speed requirements are seldom above 1-5 kHz. Since all of the devices we shall review are capable of operation at these speeds and below, the choice among the various devices is solely one of switching volt-ampere capability versus device/system cost.

We can classify power semiconductor switching devices into two broad categories: continuous drive devices and latching devices. Continuous drive devices require a continuous control signal, either a gate terminal voltage or a gate terminal current, to maintain forward or on-state conduction. Power devices that require continuous control are: the power bipolar junction transistor (BJT), the power Darlington BJT, the power MOS (metal-oxide semiconductor), field effect transistor or MOS-FET, and the insulated gate transistor or IGT*. Latching power devices need only a gating pulse signal to switch states. These devices include: the semiconductor controlled rectifier (SCR) or thyristor, the gate-turn-off thyristor (GTO) and the MOS controlled thyristor (MCT).

All the devices mentioned above, both continual control and latching, are normally off devices. That is, they remain in the voltage blocking or off-state until a suitable gate signal is applied. There are power semiconductor switching devices that are normally-on devices, such as the power junction field effect transistor (JFET) or static induction transistor and the field controlled thyristor (FCT). But these devices require more complicated gating circuitry and in general are not utilized in motor drive applications.

*The IGT has several commercial name variations, such as: COMFET, GEMFET and bipolar-mode MOSFET.

Device Descriptions

The physical cross-section, the device thermal voltage-current characteristic and the device circuit symbol for the power switching devices considered here are given in Figure 5.7-1 [PS1]. The principles of operation for these devices are as follows:

Bipolar Junction Transistor (BJT)

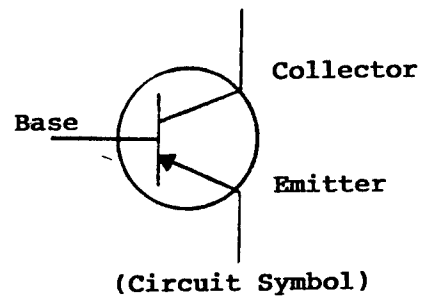
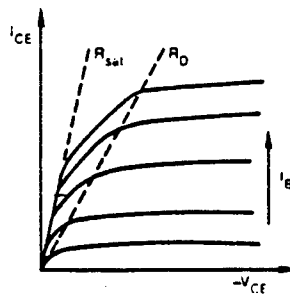
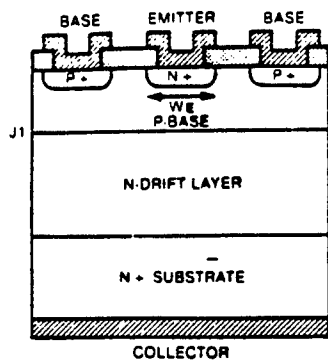
Injected majority carriers (holes in a NPN device and electrons in a PNP device) in the central base region, due to the flow of base terminal current, control the energy barrier between the emitter and base regions of the device. The emitter-base barrier is lower in proportion to the amount of base terminal current allowing base region minority carriers to flow over the emitter-base barrier, traverse the base region and be swept into the collector-base barrier region. This flow of base region minority carriers from the emitter to the collector, constitutes emitter-collector current. When a sufficient amount of base current is present the flow of emitter-collector current saturates at a value determined by the external circuit and the device is said to be "on." Removal of the base current will raise the emitter-base barrier to a point that the flow of emitter-collector current (base region minority carrier flow) ceases and the device reverts to its blocking state wherein the "blocked" voltage is dropped across the collector-base barrier regions.

Darlington

A Darlington device is a name (after the inventor S. Darlington) given to the cascade connection of two BJT's shown in figure 5.7-1 (b). Note that the emitter current of the input device is the base drive current of the output device. Thus the base current amplification factor of the combined devices is the product of the base current amplification factors of the two individual devices. The Darlington connection enables higher levels of device output current for a given level of base drive but at a slight sacrifice in device speed (since base region majority carriers in the output device cannot be effectively removed during the "switching-off" operation).

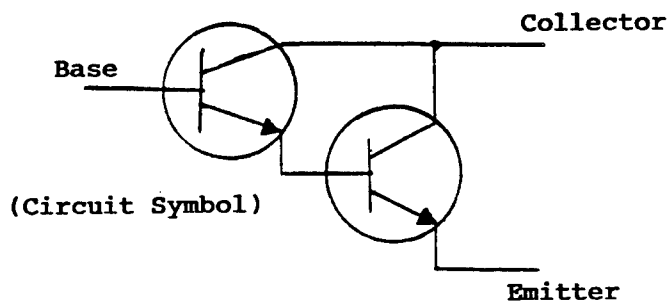
MOSFET

Power MOSFET devices are unipolar devices in that there is only majority carrier current flow from the source terminal to the drain terminal. A sufficient level of gate-to-source voltage will "invert" (i.e., change



Power Bipolar Transistor

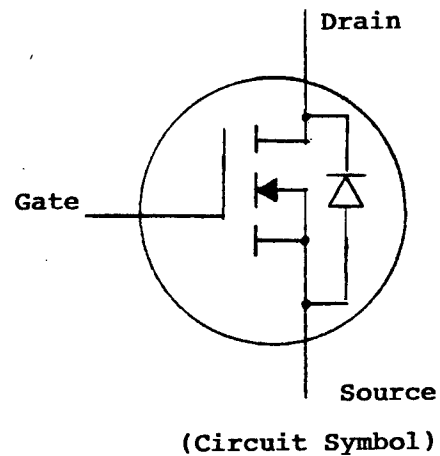
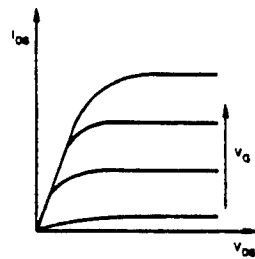
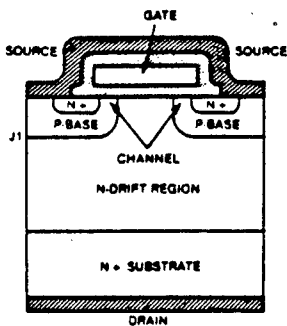
(a)



Power Darlington

Cascade Connection of Two BJT's

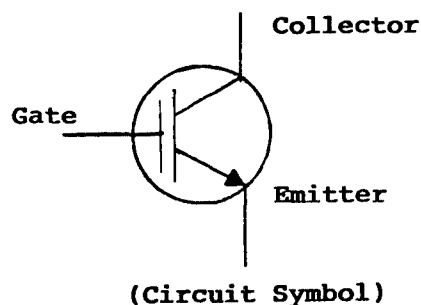
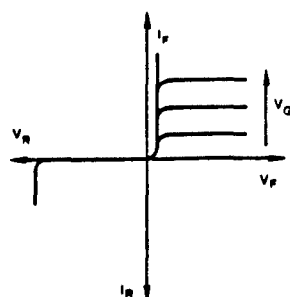
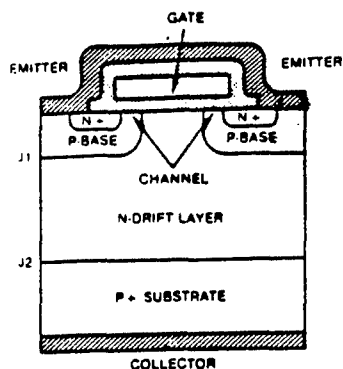
(b)



Power Mosfet

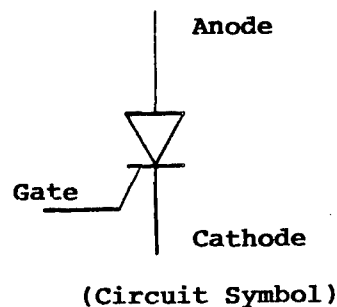
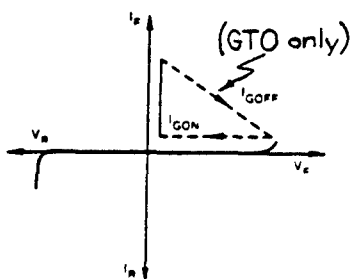
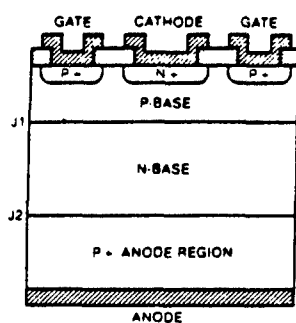
(c)

Figure 5.7-1. Power Semiconductor Devices,
characteristics, and Circuit Symbols



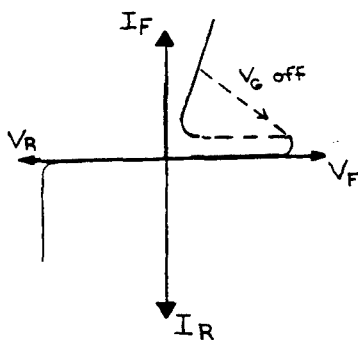
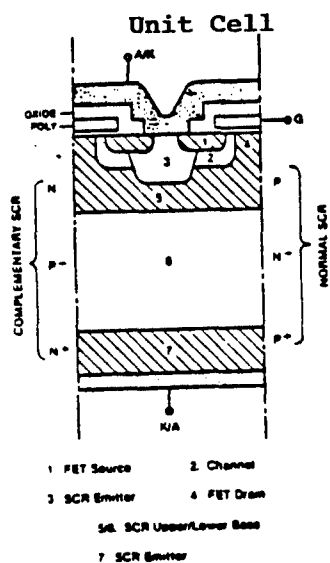
Power MOS-IGT

(d)



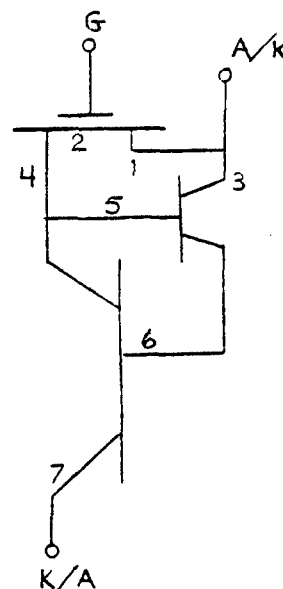
SCR and GTO

(e)



MCT

(f)



No accepted symbol developed as of yet

Figure 5.7-1. Power Semiconductor Devices, characteristics, and Circuit Symbols (Continued)

from p-type to n-type or vice-versa) a "channel" region under the gate metal-oxide. This channel region then completes a current flow path between the source and the drain terminals. Note that the current path is lateral across the surface channel and then vertical to the drain on the device bottom surface. Source drain current will flow up to the point of channel "pinch-off" due to insufficient inversion channel carriers at the drain end of the channel. If the channel inversion is strong enough, the level of source-drain current will be determined by the external circuit and the device is said to be "on." Removal of the gate-source inversion voltage depletes the conduction channel of mobile carriers and turns the device "off." The device voltage is then dropped or blocked across the reversed biased p-n junction marked J1 in figure 5.7-1(c).

Insulated Gate Transistor (IGT)

An insulated gate transistor is a unique combination of a vertical power MOSFET device and a bipolar pn junction. The device, shown in figure 5.7-1(d) is fabricated almost exactly the same as the power MOSFET structure of figure 5.7-1(c), save for collector/drain substrate material. In an IGT the carrier flow (injected from the source/emitter terminal) is collected by an opposite type layer of semiconductor material. This collection, which requires carrier-to-carrier recombination, is slower to "turn-off" than pure majority carrier flow (as in a pure power MOSFET), but it takes place at lower forward voltage drop (due to injected carrier conductivity modulation). Thus for the same forward voltage, an IGT can handle higher through or "on" currents than can a similarly sized power MOSFET. In many respects an IGT can be considered as a MOS gated BJT; combining the best features of both the power MOSFET and the power BJT: the voltage gate control of the MOSFET and the low on-resistance of the BJT.

Silicon Controlled Rectifier (SCR) and Gate-Turn-Off Thyristor (GTO)

The cross sectional view of a gate-turn-off thyristor varies only slightly from that of a standard SCR. Both devices are four-layer devices that can be thought of as two three-layer BJT's regeneratively connected such that

each device's output "feeds" the other's input. See figure 5.7-1(e). In both devices a sufficiently large gate current will trigger the lower npn BJT into forward conduction just long enough for it to trigger the upper pnp BJT into forward conduction. Since the upper pnp BJT collector drives the lower npn BJT base, a condition of regenerative self drive can be reached in which anode to cathode current will be self sustaining and the original gate drive can be removed. When this occurs the devices are said to be "latched on." This regenerative "on" state can be broken by simple interruption of the anode-cathode current, by some external means, that allow the BJT barriers to recover to their blocking state. In the GTO structure the gate contact region is sufficiently large in comparison with the cathode current emitting region such that simple gate current reversal (or the removal of the lower npn BJT base region majority carriers) is enough to break the regenerative on-state and shut the device "off." In most GTO structures the reverse gate current pulse that shuts the device off must have a magnitude of between $1/5$ to $1/3$ of the magnitude of the anode-cathode through current. This may seem like a high value for a "control" signal but on a power basis, since the gate-cathode voltage level is low during turn-off (approximately 10-20 volts), it is indeed low. GTO turn-off circuitry consumes far less energy than forced commutation circuitry for a similarly rated standard SCR.

MOS Controlled Thyristor (MCT)

The MOS controlled thyristor is a new device [PS 2, PS 3] that is not yet in commercial production. It is almost an ideal power device. It combines the latching capability of the SCR with the control ease of the power MOSFET or IGT. Since it is a four-layer device, it can be triggered into a regenerative "on" or latched state by means of standard forward gate current. The unique aspect of the MCT, however, is its ability to "turn-off" by means of a surface channel MOS shorting device. An inversion channel, due to an applied turn-off MOS gate-cathode voltage, can be formed between the device cathode, region 1 in Figure 5.7-1(f) and the collector of the anode side pnp BJT, region 4 and 5. Current through this channel shunts around the cathode side npn BJT and weakens the regenerative action of the two BJT structures. If enough current is shunted

through the turn-off channel, the cathode-anode through current can be totally interrupted. Recent experimental data [PS 4] has indicated that this effect can be used to interrupt forward current densities of over 2000 A/cm² with gate-cathode turn-off voltages of 15V. These values are expected to increase in future devices.

Comparison of Forward or "On" Characteristics

A major contributor to the heat generated in a power semiconductor switching device is due to the on-state forward drop. Thus a fundamental comparison between switching devices can be made by examining the forward characteristics of the different devices. A theoretical comparison [PS1] of 600 volt blocking devices is shown in figure 5.7-2. The level of on-state current density for a given level of forward drop clearly favors the MCT latching device for forward voltages of 1.0 volt or more. GTO forward current densities would be even higher than those of the MCT, in both cases for equal values for forward drop. Since the price of a mature technology device depends primarily on the chip area it always enjoys a cost advantage on an equal current capability comparison to continuous control devices.

Comparisons of Motorola existing, commercial devices [PS 5] of approximately equal ratings are given in table 5.7-1 and figure 5.7-3. Here again we see the inherent advantage of latching devices. Both the GTO and the SCR, eventually, can support higher levels of current at given levels of forward drop. This in terms of choosing a switching device for low frequency switching applications (≤ 5 kHz), latching devices have a clear price/performance advantage. And, among the latching devices, the GTO, at present, has the advantage due to its gate control ability. But the MCT has the potential to be the clear winner in the future, again, due to its voltage/gate control ability.

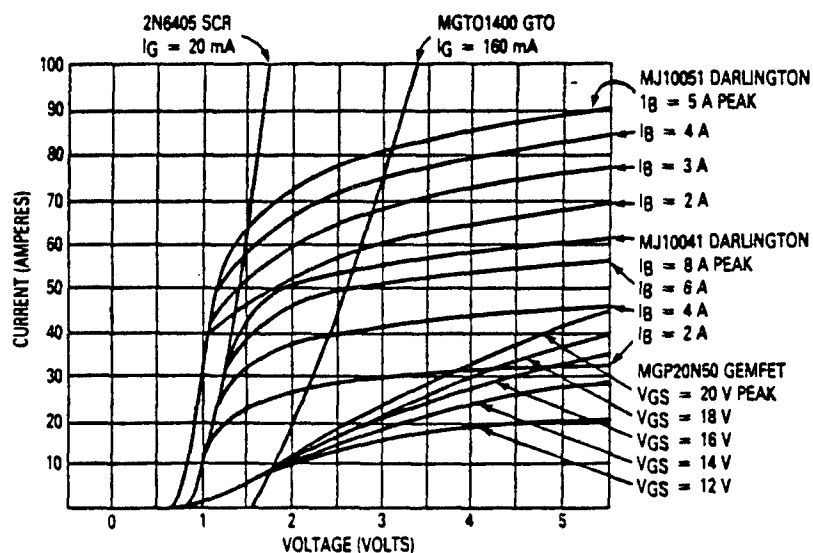
Projections and Device Trends

A recent GE projection [PS 6] of device switching volt-amp capabilities for power MOSFET's, IGT's, and MCT's is given in figure 5.7-4. This

TABLE 5.7-1 VOLTAGE, CURRENT, AND POWER CAPABILITY
OF HIGH VOLTAGE SWITCHES

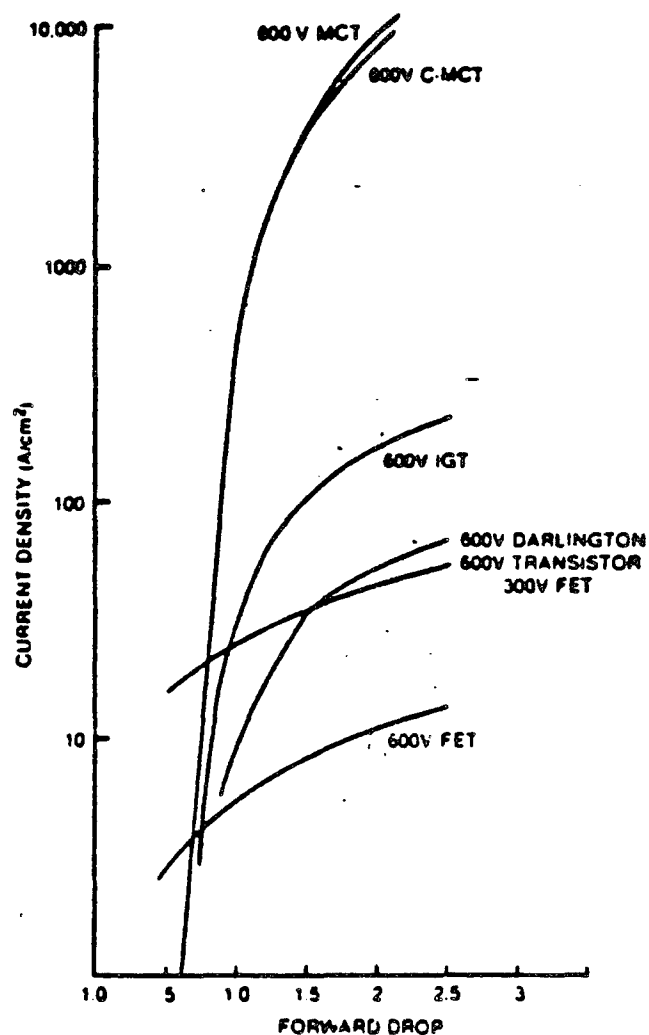
Device	GTO MGTO1400	Darlington		GEMFET MGP20N50	SCR 2N6045
		MJ10041*	MJ10051*		
Package	TO-220AB Case 221A-02	Case 353-01	Case 346-01	TO-220AB Case 221A-02	TO-220AB Case 221A-02
Die Size (Mils)	210 ²	2 x 264 ²	4 x 264 ²	126 x 182	150 ²
I Density (A/mm ²)	7	1.4	1.4	3.5 To 7	11.4
θ_{JC} (°C/W)	1	0.5	0.25	1.25	1.5
θ_{CHS} (°C/W)	1	<0.1	<0.1	1	1
I _{Surge} (A)	200	125	250	50 To 100	160
I _{Operating} (A)	50	25	50	30	95
I _{Continuous} (A)	18	37.5	75	20	16
Voltage (V)	1400	900	900	500	800
DC Watts @ 80 °C	45	140	280	56	30
T _J max	125	150	150	150	125

*MJ10041 includes 125 x 150 and 70 x 150 diodes. MJ10051 includes 250² and two 70 x 150 diodes.



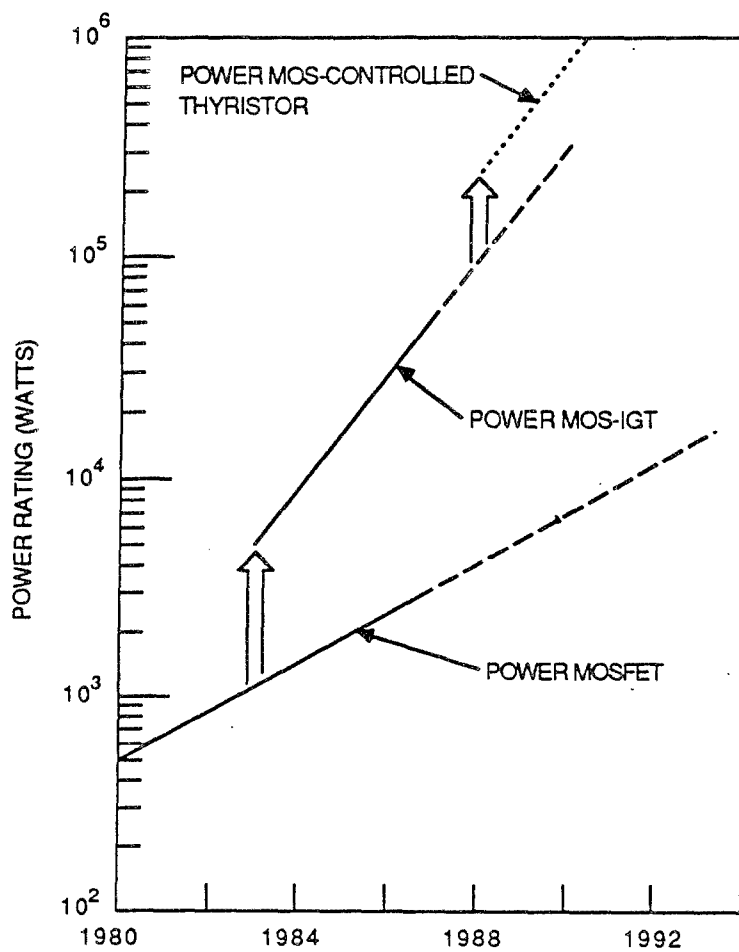
Forward Conduction Characteristics
0.5 V/Div., 10 A/Div. T_C = 25°C
P_w = 300 μs, f = 60 Hz

Figure 5.7-2. Forward Voltage Drop Versus Current
Density For Various Power Semi Conductors



Comparison of high gain turn-off device forward drop. The IGT and MCT are calculated based on the same identical doping and life-time profiles.

Figure 5.7-3. Forward Conduction Characteristics For Various Power Semiconductors



The increase of the power handling capability of power MOS devices with progress in technology and the introduction of new device types

Figure 5.7-4. Power Capability vs. Time For Various Power Semiconductors

figure clearly shows the advantage of IGT's over power MOSFET's and MCT's over IGT's. And that these advantages are expected to continue in the future.

We conclude that latching power semiconductor devices have a clear price/performance advantage over their continual control counterparts. And that, among the latching devices, the MOS controlled thyristor has the greatest potential.

5.7.1.4 Magnetic Materials

A permanent magnet is used to create a steady magnetic field in some region of space. It produces the same effect as an electromagnet but the permanent magnet requires no external source of power after its initial magnetization. The permanent magnet is said to have a higher coercive force than the electromagnet. Remanance and coercive force are the two properties which are used to measure the quality of any magnet. More often they are referred to as B and H respectively. B is typically measured in gauss and H is typically measured in oersteds. The overall energy of a permanent magnet material is measured as the product of B and H in millions or Megagauss oersteds (MGOe). The field of the permanent magnet may be used to exert a force on a current carrying conductor, as in a motor, or to induce an electromotive force (EMF) in a moving conductor, as in a generator, or to exert a force on a magnetized or magnetizable body.

Magnetic materials as applied to motors and generators can be divided into two classifications: those magnets which are electromagnets and those which are permanent. An electromagnet, in most cases, must have the capability of reversing the polarity of its field at high frequencies, whereas the permanent magnet never changes the polarity of its field. The switching in an electromagnet requires that the magnet have special characteristics. These special characteristics are typical in soft magnets; they have high magnetization, low coercive force and low core loss. The low coercive force enables the magnetic field to be realigned with very little energy loss. The two principal material requirements are a high working flux density and a low energy loss when the magnetic flux is changed. Silicon steel is the material

used most often for electromagnets. In order to enhance these characteristics the steel is often made in very thin sheets and laminated. This reduces the core loss. Core loss is the loss encountered in changing the field; this means a rearrangement of molecules, which causes eddy currents to flow, which in turn opposes the desired flow of current and subtracts from it. Core losses occur in average silicon steel at about 2.5 watts per pound of steel. Research is continuing in an effort to reduce core losses; newly developed types of silicon steel have reduced core loss by 20 percent. Each improvement in core loss allows the steel to be used at a higher level of magnetic flux density thereby allowing a reduction in the amount of steel used and reducing the size and weight of electrical machinery (see Figure 5.7-5).

Silicon steel has a crystalline molecular structure. This type of structure is more prone to core loss than an amorphous material. This fact has promoted research in the manufacture of so called "glass" electromagnet cores. The amorphous metals can reduce losses and thus increase efficiency. One disadvantage to the amorphous steel is that it is more expensive to produce than its competitor. The expense comes in the manufacturing process - the molten steel must be cooled extremely rapidly on the order of millions of degrees per second. As a result, to achieve this rate of cooling the material can be made only 1 to 2 mils thick. This, of course, is made into a usable state by laminating many layers. Another disadvantage is that the "glass" metal tends to have a lower maximum induction level capability.

The first permanent magnets, used nearly 600 years ago, were ferrosic oxide magnets or lodestones. The first artificial permanent magnets were made from special forms of iron and steel. For many years, until 1910, hardened carbon steel was used; now carbon was quenched from 800°C in the hardening process which developed a surface skin of glass-hard material which was magnetically superior to the rest of the body.

This discovery led to the use of quenched layers of carbon steel laid in laminations to improve properties of the permanent magnet. With homogeneous mediums such as carbon steel there is no such effect so most permanent magnets today are made in solid form.

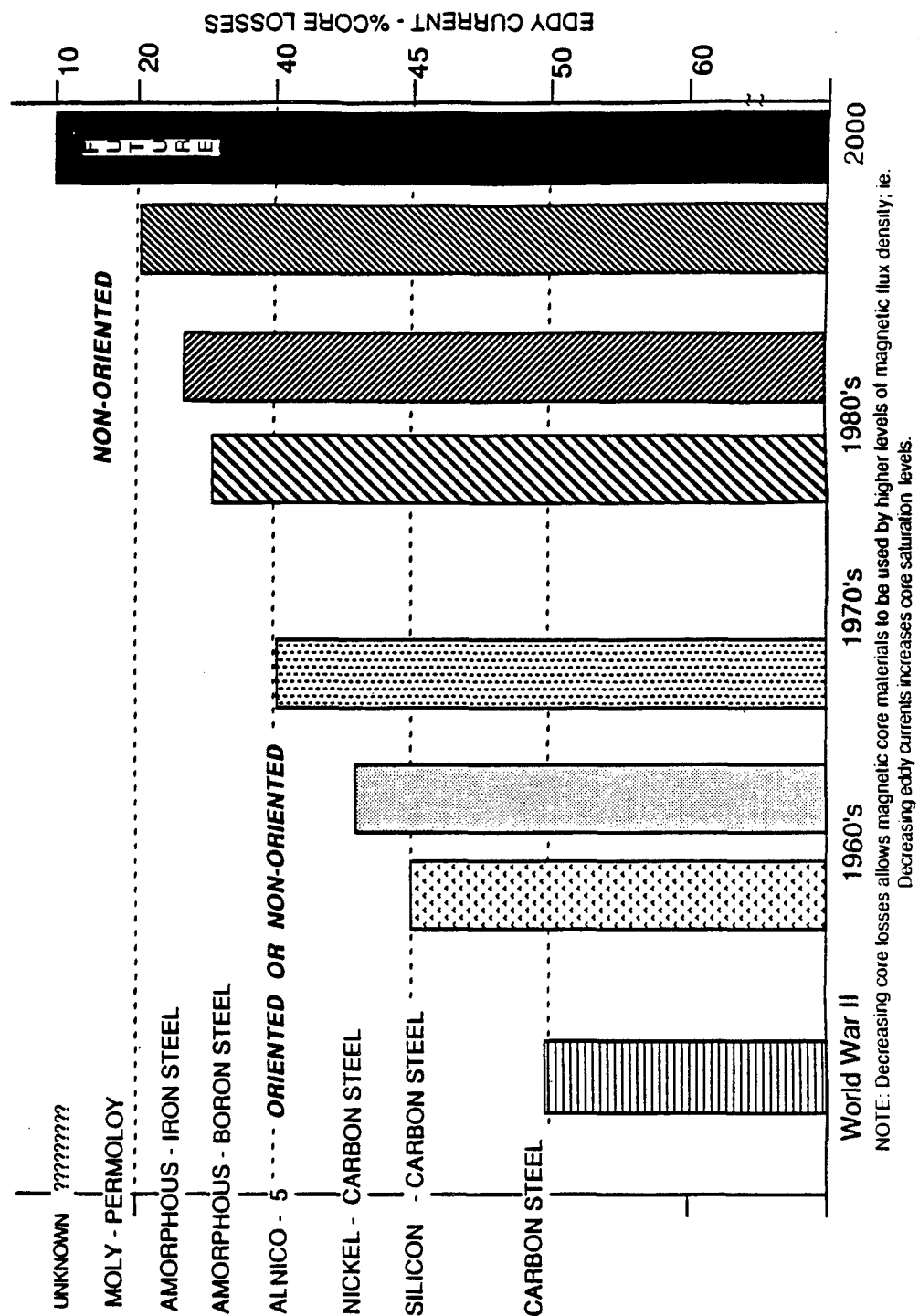


Figure 5.7-5. Trend Chart of Lamination Magnetic Materials

Figure 5.7-6 shows several popular compounds which are used for permanent magnet materials. Chromium-cobalt-iron permanent magnets have been developed for purpose of reducing manufacturing cost. This compound is ductile enough to be cold formed at room temperature, whereas the more brittle than Alnico and ferrite must be cast and ground into final shape. In addition the FeCrCo and Alnico achieve about a 5MGOe energy level but the FeCrCo has much less cobalt, the most expensive element of the compound.

Although cobalt is considered rather expensive and a rare earth metal, it is used widely in permanent magnets today. Compounds utilizing samarium and cobalt have been developed over the last 15 years which have some of the best magnetic properties. Typical BH energy products are in the range of 16 to 30 MGOe depending on the particular alloy. At the higher maximum energy products there are often trade-offs; for example, the typical cost of a samarium cobalt magnet is \$50-100 per pound. By substituting copper for some of the cobalt in SmCo5, high coercivities can be obtained after suitable heat treatment and can be manufactured by casting. The copper, however, lowers the saturation magnetization level, but by adding small amounts of iron, saturation magnetization levels can be improved at the expense of sacrificing coercivity. With the addition of zirconium in small amounts, some of the best materials have been made within the basic samarium cobalt family of compounds.

Early in the 1980's, research began on compounds without cobalt and with improved overall energy products. In the past development of stronger magnets relied on the addition of cobalt. Recently, compounds using neodymium, boron, and iron (NdFeB) have been developed and are available in limited commercial applications. The neodymium is still considered a rare earth metal; however it exists in far greater quantities than rare earth cobalt. Consequently, the NdFeB compounds can be manufactured at less total cost per pound. Various versions of this compound have produced net energy products as high as 50 MGOe (see figure 5.7-7). Use of the new compound promises to reduce weight of future permanent magnet motors by 20 to 30 percent; a similar reduction is expected in size (approximately 20 percent).

One major disadvantage of neodymium-iron-boron permanent magnets is that they have a very low curie temperature by comparison to samarium cobalt magnets. The curie temperature is the temperature at which the thermal activity in the

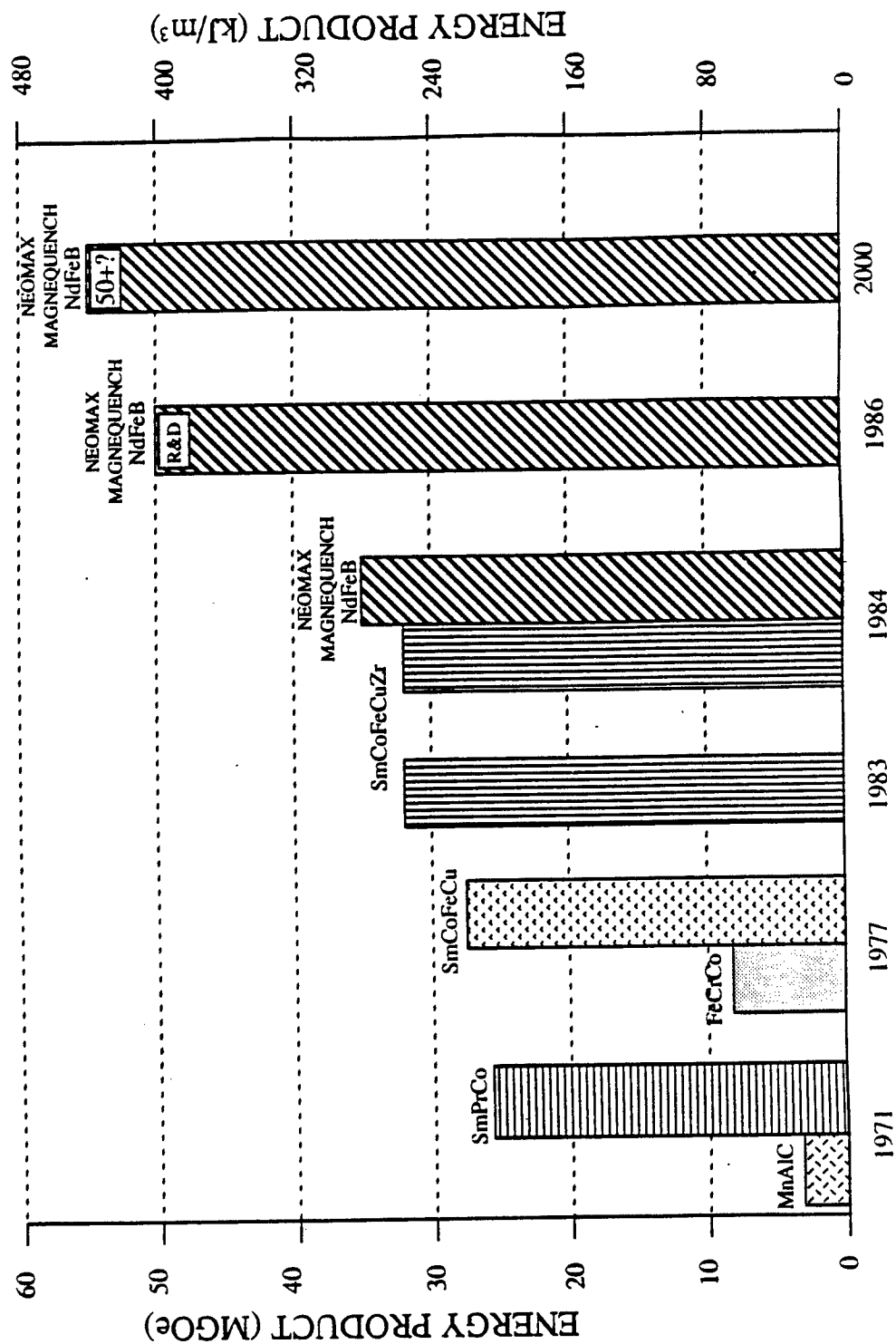


Figure 5.7-6. Trend Chart for Rare Earth Magnetic Materials

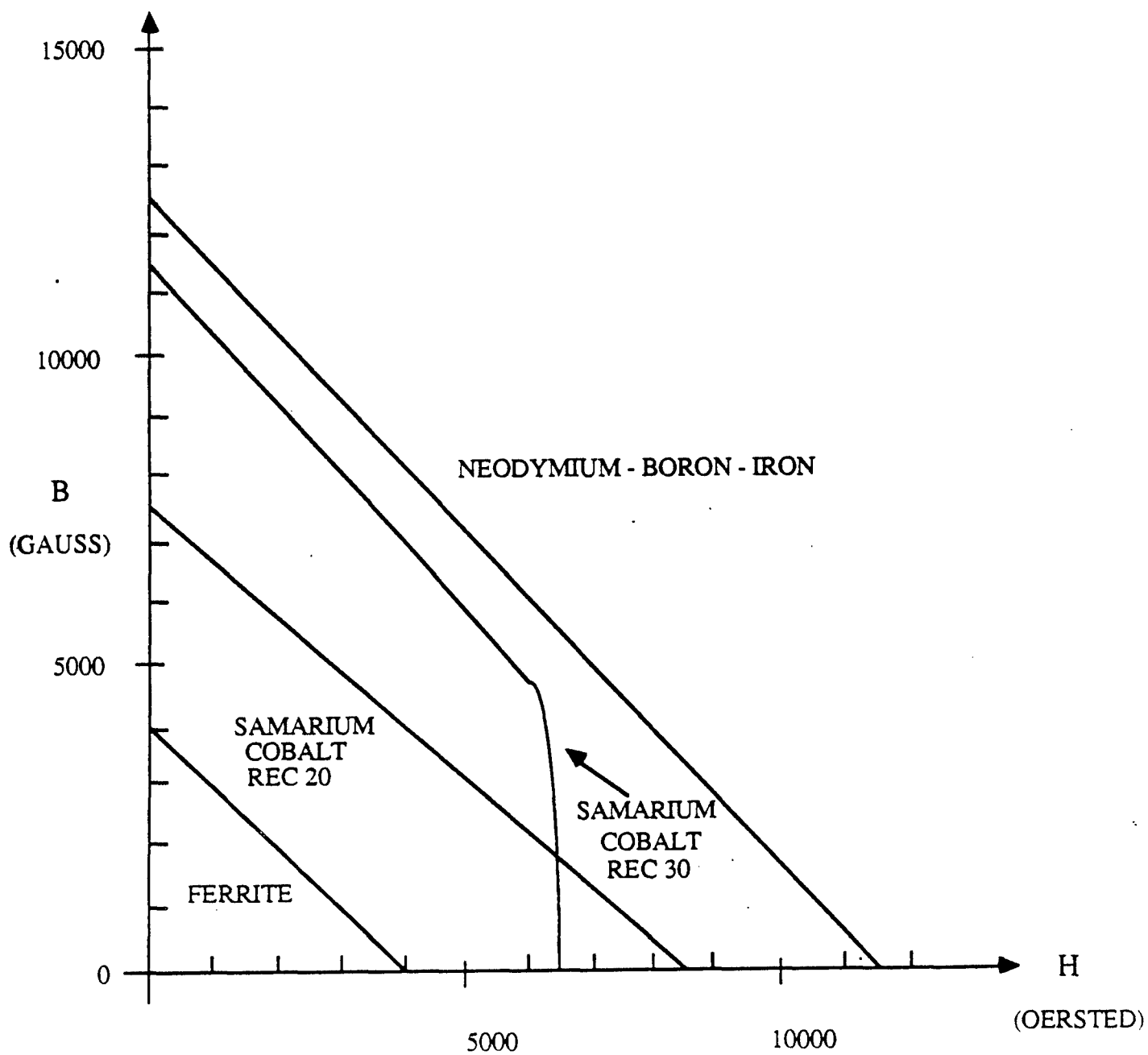


Figure 5.7-7. Demagnetization Chart of Magnetic Materials

material exceeds the magnetic field. The result is that the thermal activity or random movement of atoms creates new magnetic fields. The net result of this being a total cancellation of a dominant magnetic field. Once a magnet reaches its Curie temperature, permanent damage will occur. NdFeB permanent magnets have a curie temperature between 125° to 150°C. Magnetic energy drops off severely at relatively low temperatures approaching the curie temperature.

Permanent magnets, combined with higher power semiconductors and microprocessors, are revolutionizing electric drive systems. The AC permanent magnet (brushless DC motor) is rapidly evolving and will replace most electrically excited machines. Permanent magnet motors using magnetic materials such as samarium cobalt and neodymium-iron-boron are proving to be state-of-the-art drive actuation, and propulsion technologies for today and tomorrow. Magnetic materials will continue to play an important role in motor and generator applications for future electric propulsion systems. Further use of these high energy compounds as frictionless bearings, motor laminations, etc...will become more and more popular.

5.7.1.5 Controls

Control in the context of an electric drive can be subdivided into two major power-level defined categories: control as related to the transfer of information and logic level control signals (i.e., low power control), and control as related to the transfer and conversion of traction power (i.e., high power control). We associate the first control category with the Electronic Control Unit or ECU and we associate the second control category with Power Conditioning Units or PCU's. The signal and power level interconnections of ECU's and PCU's for three types of configuration drives are shown in figures 5.7-8, 5.7-9, and 5.7-10. Note that in the DC field control blocks we have included the parenthetical description (PCU) to indicate that field control is in actuality a low power (1-3% of the machine power) transfer - conversion process. Each functional control unit package, ECU and PCU contains components that are in a continual state of evolution. The size, weight, performance, reliability, and cost of both the ECU and the PCU continue to improve with time. The primary impetus for this improvement is the integration of electronic functions in silicon integrated circuits.

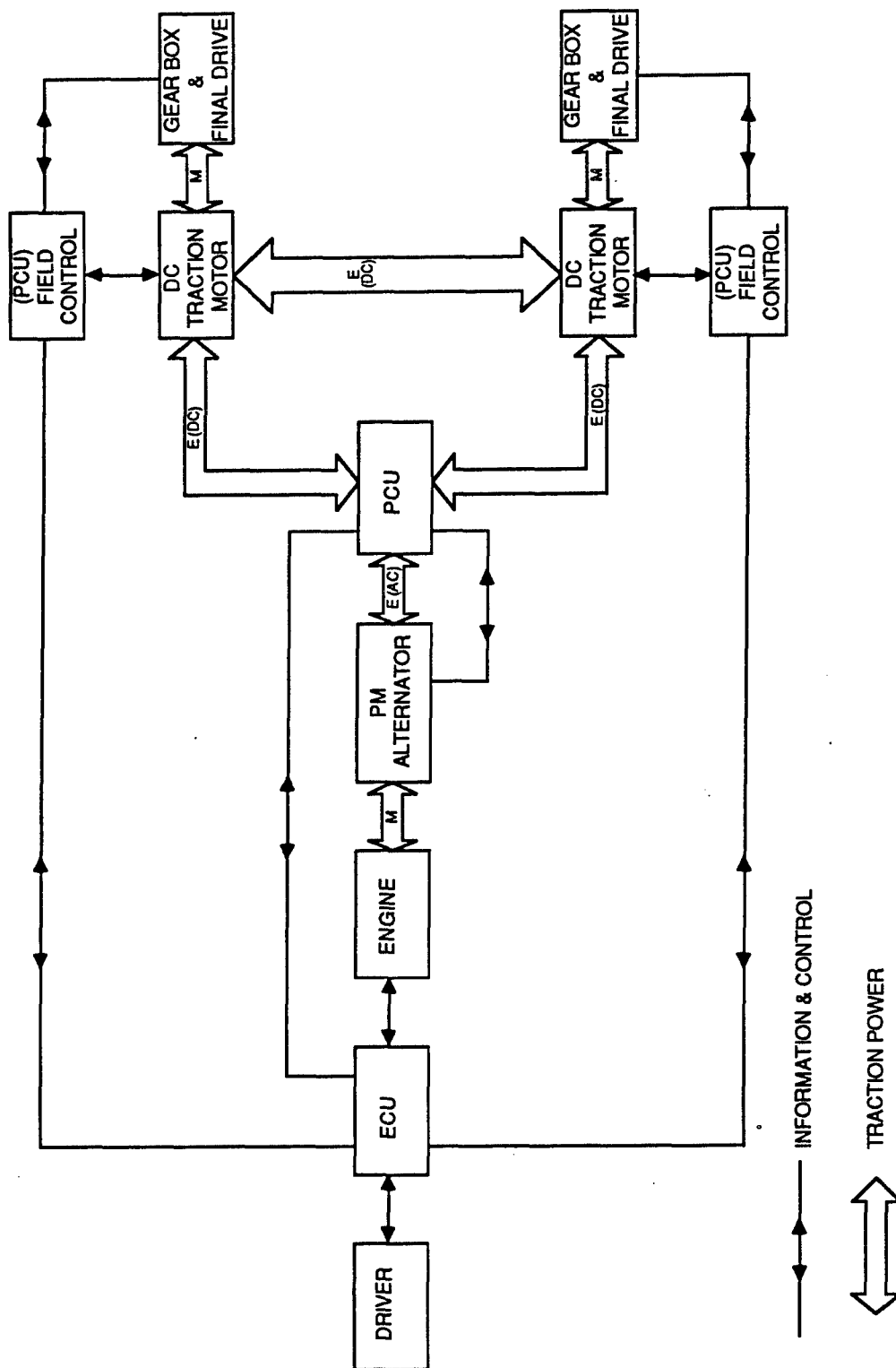


Figure 5.7-8. Block Diagram For DC Traction Motor System

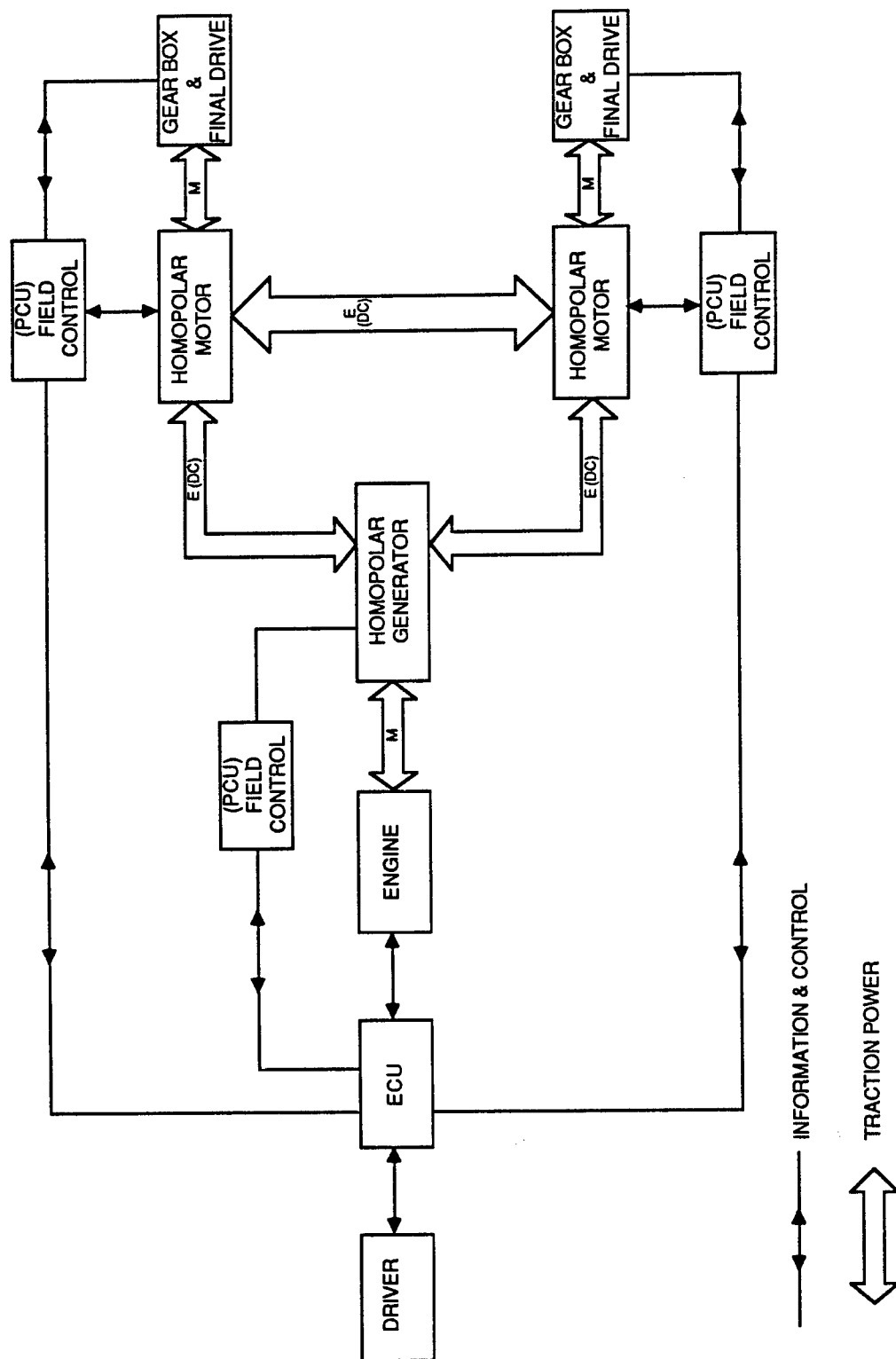


Figure 5.7-9. Block Diagram For DC Homopolar System

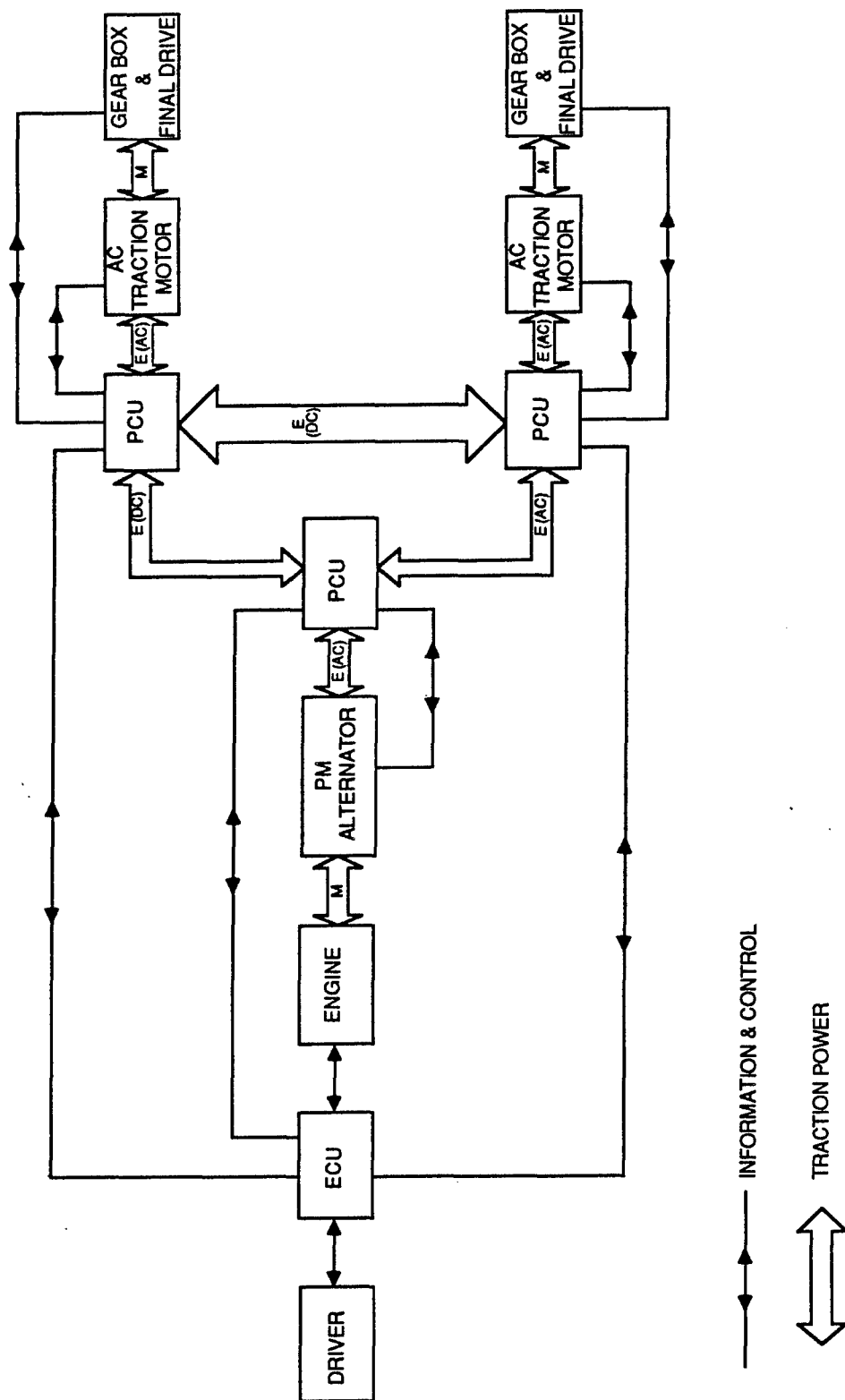


Figure 5.7-10. Block Diagram For AC PM Traction Motor System

Electronic Control Unit (ECU)

Electronic control units are by design small computer systems. Serial or parallel input/output (I/O) lines connect the ECU with the vehicle driver and the major drive train components. Command inputs from the driver and status inputs from the drive train components dictate various "sorted program" responses that are then transferred over the I/O lines, back to the drive train components. Real time feedback signals from the components enable the ECU to both monitor the operation and alter its original commands to maintain a form of optimal control, maximum fuel economy, etc. The ECU also coordinates system protection functions such as component shutdown due to excessive temperature.

In first generation electric drive systems, such as the GDLS EVTB wheeled vehicle, the ECU consisted of ten printed circuit boards containing memory, signal conditioning, and discrete logic large-scale integration (LSI) chips and medium scale integration (MSI) chips and a first generation 8-bit microprocessor, the Motorola 6800. A second generation of the EVTB ECU would consist of a single board containing several very large scale integration (VLSI) chips and a third generation 16-bit dedicated control single-chip microcomputer such as the Intel 8096 or the Motorola offshoot, the 68200. A dedicated control single-chip microcomputer has on-chip I/O processing, A/D and D/A, interrupt line control, event-time counters, memory, and both volatile (RAM) and stored program (ROM). These auxiliary functions would have to be provided by additional special purpose chips if general purpose micro-processors, such as the 8086 and 6800 were used.

To indicate the trends in microprocessor/microcomputer capability we include figures 5.7-11 and 5.7-12, taken from reference [c1]. Figure 5.7-11 shows the number of metal-oxide semiconductor (MOS) transistor that have been utilized to form a single VLSI chip as a function of the year of the chip's entry into the commercial marketplace. The control single chip microcomputers mentioned above, the 8096 and the 8200, are slightly more complicated and thus their complexity is slightly greater than their general purpose microprocessor parents, the 8086 and 68000, respectively.

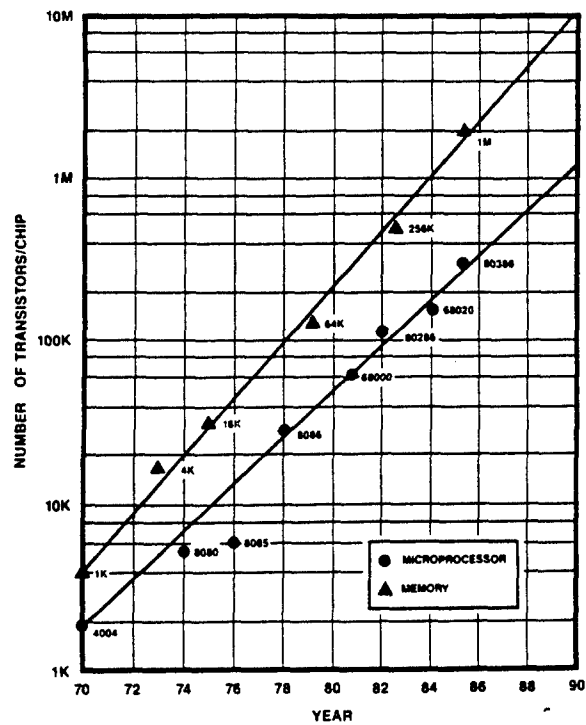


Figure 5.7-11. Number of Transistors Per Chip Versus Time

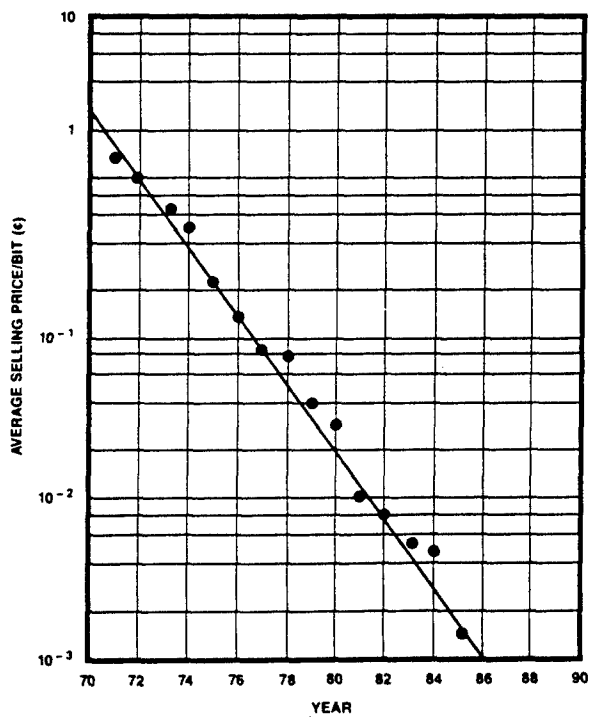


Figure 5.7-12. Cost of Computing Power Versus Time

Integration in silicon not only rewards the user in computing power per chip, but also in money saved per unit of computation. Figure 5.7-12 shows a steady year by year decline in the cost per bit of chip based digital information with no apparent leveling off in the rate of decline over a 16-year period. With greater and greater levels of integration (chip density) forecast for the future, we expect the "economy of scale" trend to continue into at least the mid 90's. At this time, fundamental limits in silicon MOS transistor operation will be reached and new device structures will be required to continue the trend in ever increasing chip densities. Based on past performance and innovations it would be foolish to assume that such new structures will not be developed.

Power Conditioning Unit (PCU)

The PCU function, as depicted in figure 5.7-13, can be broken down into three interconnected sub-functions: a signal level (i.e., low power) control communication function, a level transfer (i.e., signal voltage level to traction power voltage level) power device drive function and a power device traction power level switching function.

The first function can be thought of as a low-level ECU function. Command signals are received from the main ECU and status signals are received from the power switch network, the traction motor and gear box, local computations are made and firing signals are sent to the power semiconductor driver networks. Local feedback signals may modify the switching drive signals or indicate abnormal response. Local corrective action can be taken, such as PCU shut-down, or warnings can be relayed to the main ECU. These "smart" functions can and will take advantage of the same advances in VLSI circuitry as the main ECU. The local ECU will become a dedicated microcomputer.

The voltage level shifting and power device drive functional box shown in figure 5.7-13 has in the past been constructed with discrete semiconductor devices. In the GDLS EVTb PCU just the power device gate driver alone required an entire printed circuit board. But, just as in the ECU, silicon integration will enable a massive reduction in parts count and space claim for this functional block.

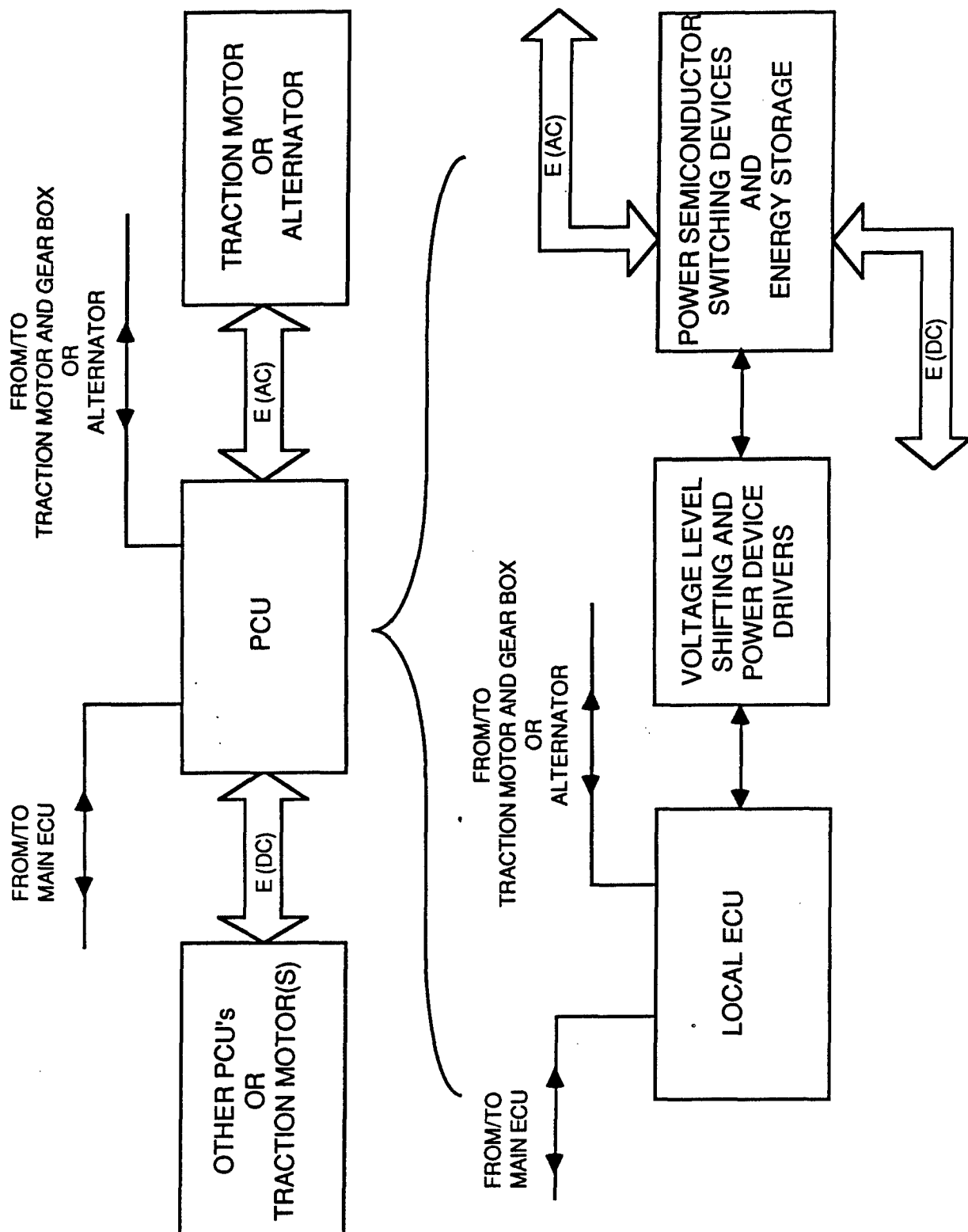


Figure 5.7-13. PCU Functions

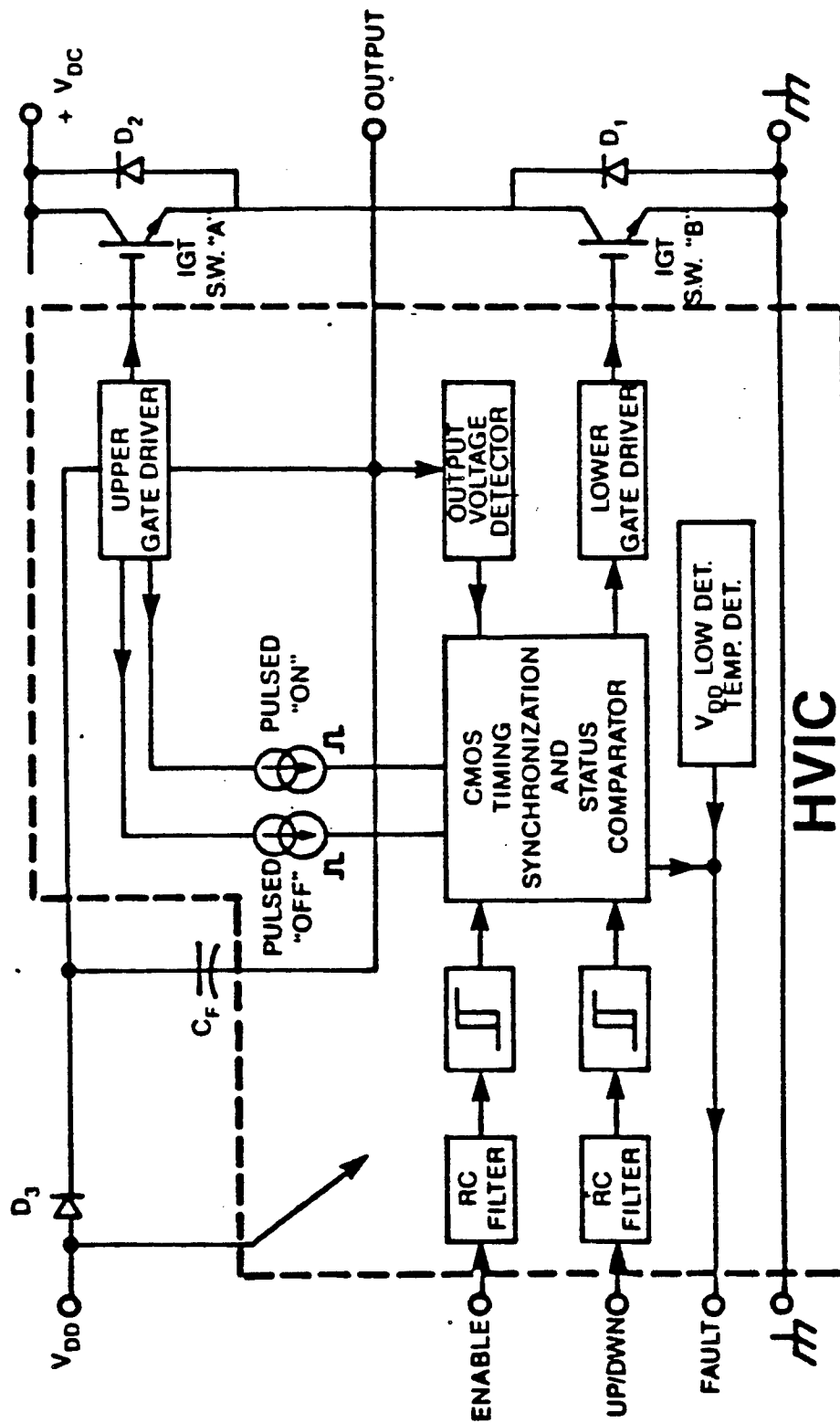


Figure 5.7-14. High Voltage Integrated Circuit (HVIC) Chip Diagram

Many manufacturers have developed high-voltage power integrated circuits (HVIC's) that can be driven directly by logic level signals from microcomputers and which will drive directly the gates of power switching devices. Figure 5.7-14 is a block diagram of one such IC developed by General Electric [c2]. All of the functions enclosed in the dashed box have been integrated into a single silicon chip. This particular chip will work up to DC bus voltage levels, V_{dc} in figure 5.7-14, of 500 volts.

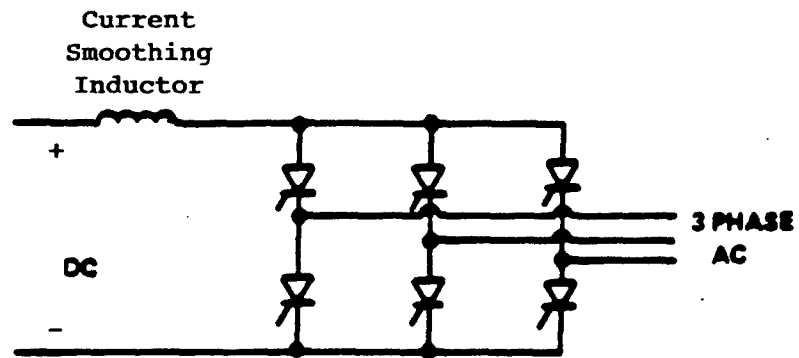
The chip is shown driving insulated gate transistors (IGT's) but the chip output could easily be reworked to drive other power devices. For very high power devices the power IGT devices shown in the figure could, as an intermediate measure, be reconnected to drive individual gate leads in a Darlington type arrangement.

Use of HVIC's will clearly: reduce interface circuit size, economically justify more interface circuit diagnostic functions, increase interface circuit reliability, and lower the total cost of the interface circuit function.

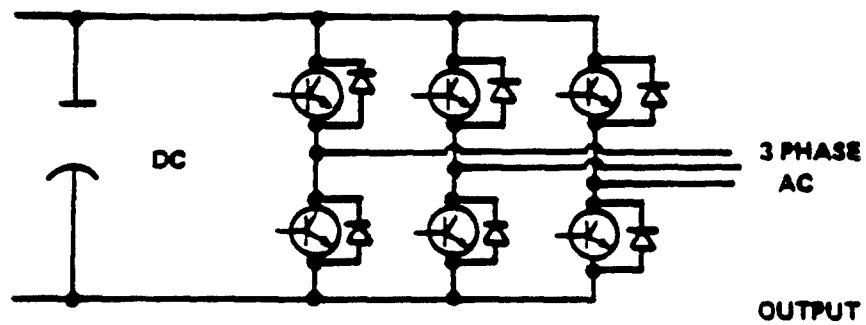
The last block in the breakdown of the PCU function is figure 5.7-13 contains the power components of the PCU: the power semiconductor switching devices and energy storage elements. There are two fundamental arrangements of power switching devices in a AC/DC power conversion circuit. These two arrangements depend on the type of "smoothing" energy storage element that is used on the DC side of the power switching devices. If an inductance is placed in series with the DC input (output) line of the power device network the power converter is termed and a "current source" converter. This is because the DC network, as seen from the AC side of the converter, appears as a slowly varying DC current source, due to the current smoothing effect of the inductor. If a capacitance is placed in shunt with the DC input (output) line of the converter the power network is termed a "voltage source" converter. In this case the DC network, again as viewed from the AC side of the converter appears as a slowly varying DC voltage source, due to the voltage smoothing effect of the capacitor.

Typical DC linked 3 phase AC current source and voltage source converter networks are shown in figure 5.7-15. The current source converter in figure 5.7-15(a) is an AC "line commutated" unit. That is the current reversal and the needed reverse bias voltage for the thyristor devices are both provided by the AC network load or source. The voltage source converter in figure 5.7-15(b) is a "forced commutated" unit. That is current is forced to zero in each of the power transistor devices by transistor base current control, not by the AC network. The transistors in the voltage source converter in figure 5.7-15(b) can only block voltage in one direction due to the reactive current return anti-parallel diodes in each leg of the converter. Thus power can only flow from the DC network to the AC network in this unit and the device is more correctly referred to as a voltage source inverter or VSI. The SCR's in the current source converter of figure 5.7-15(a) can block voltages of both polarity and thus power can flow in both directions from DC to AC (inversion) or from AC to DC (rectification) in this unit. The generic name "power converter" is best suited for their device.

Both current source and voltage source converters will benefit from the continual improvement in commercial power semiconductor characteristics (see section 5.7.1.3 of the report) that is being demonstrated by both domestic and foreign (primarily German and Japanese) manufacturers. The greatest level of improvement will come in voltage source units. This will be due to both improvements in gate control/commutate devices such as the bipolar junction transistor (BJT), the insulated gate transistor (IGT) and the MOS controlled thyristor (MCT), and improvements in energy storage capacitors. Current source converters can and will be improved by reduction in the size of needed auxiliary force commutation circuits, needed when the AC side of the converter has insufficient energy to line commutate the switching devices, and in reductions in the size of the switching losses in the switching devices. It will be hard to improve the size of the required smoothing inductor. The only major improvement in the inductor will be in the cooling of the unit.



(a) Current Source Converter



(b) Voltage Source Converter

Figure 5.7-15. Current Source and Voltage Source Converters

Conclusion

We estimate that future ECU's will be single board assemblies that will make extensive use of VLSI devices and single chip control microcomputer. The reduction in volume and cost will be extensive enough to allow identical backup (redundant) ECU's to be placed side by side with primary units.

Future PCU's will also benefit from integrated circuit electronics. They will contain mini or local ECU's, high voltage integrated circuit (HVIC) power devices and advanced power semiconductor switching devices. Current source PCU's could be as small as 1/2 to 1/3 of the volume of their present day counterparts and voltage source PCU's could be as small as 1/4 their present size. Net cooling requirements will also be reduced in future PCU's, but not to the extent that the total volume can be reduced, since the primary source of heat generation will remain the loss mechanisms in the switching devices.

5.7.1.6 Commutation

In DC machines commutation is the name given to the forced reversal of the current in a rotating armature coil. If the machine is a 2N pole machine this reversal occurs N times in each coil per armature revolution. The mechanics of commutation consists of carbon brushes in series with the stationary armature terminals sliding over rotating copper commutator bars that are connected to the rotative armature windings. These brushes are placed in the magnetic neutral plane of the pole fielding windings where the induced voltage in the associated armature winding is a minimum.

Though simple to describe, commutation is a non-trivial function. The reason being the induced voltages due to the self and materials inductances of the armature winding themselves. When the current in a particular winding is completely reversed the voltage V_s that is induced in the winding due to its own self inductance L_s is given approximately by:

$$V_s = L_s \frac{di}{dt} \sim L_s \frac{2 I_o}{T_c}$$

where I_0 is the steady-state current in the coil, T_c is the commutation time (directly proportional to the commutator bar circumferential length and inversely proportional to the commutator bar surface speed), and the factor of 2 is due to the fact that the coil current is reversed from $+I_0$ to $-I_0$ or vice-versa. If other nearby coils are undergoing commutation at this same time there will be other additive voltage contributions to the total voltage induced in the coil of interest. If left uncompensated, these coil voltage terms will in general not match the resistive voltage drop in the circuit due to coil and brush conduction losses. Thus at brush departure from the trailing end of the commutator bar, there will develop excessive sparking, which will in time lead to commutator - brush destruction.

All modern day DC machines compensate for the armature coil self/mutual induced voltage by means of dedicated interpole windings that produce back emf within the coils to cancel (on the average) the coil flux generated voltages. These interpole windings are in series with the main armature current and thus are self adjusting to the level of machine drive. Also, the interpoles upon which the interpole windings are wound have sufficient air gaps that they are assured of not saturating.

Model interpole compensated DC machines are not speed limited by commutation. DC machine speed is primarily limited by the fact that the rotation element contains the power windings. Centrifugal force on these windings limits the maximum machine rotational speed. Future improvements in the mechanical construction of the rotors of DC machines may push machine speeds to the point of commutation limitations, but more effort, industry wide, is being put into electronically commutated machines, i.e., AC machinery, than there is in improving DC machine structures. The DC machine is far from dead, but it is not a subject of intense research, particularly when compared to the level of work being expended in the development of high speed AC machinery.

5.7.1.7 Mechanical Structures

Mechanical Structures encompass non-electrical components such as the case, end bells, shaft, bearings and seals required in motor and generator designs.

The investigation of technologies associated with mechanical structures indicated meaningful impact on rotating electric machinery only for the area of bearings.

Bearing systems are important to lightweight high performance rotating machinery design because bearing design can limit the life, operating temperature, and operating rotational speed depending on the specific design. Generally as insulation systems improve to allow greater operating temperatures, bearing systems must also operate at these elevated temperatures otherwise they will limit the design operational range. Also, as electrical design improvements allow greater rotational speed, resulting in reduced machinery weight and volume, bearing systems must be available that can operate at these increased speeds under load if the weight and volume reductions are to be realized.

Currently the growth of bearing technology is slow. However improvements in materials, material processes, and lubrication have been accomplished and are continuing. Advanced bearings developments that hold promise for future rotating machinery, operating at temperatures and/or rotational speeds beyond the capability of current bearing systems, include nonmetallic, composite ceramic, and magnetic bearings.

In conclusion bearing system requirements are design specific and some future applications will require improved bearing designs to realize the full potential of future electric technology improvements.

5.7.1.8 Cooling Techniques

Improved/advanced cooling techniques have potential for reducing the size and weight of individual electric machines, of the transmission cooling system and ultimately of the transmission system. Cooling systems are designed to meet varying goals and requirements and a number of trades must be considered for optimizing cooling systems. Improved cooling techniques applied to individual electric drive components can reduce the size and weight of these components, however, generally this will produce a greater cooling load on the cooling system. The cooling system may be improved by using advanced heat exchanger

design. Also the cooling system can be optimized for best installed volume and weight or minimum power demand. Also it is advantageous, from the standpoint of minimizing installed volume, to integrate the transmission and engine cooling systems into one main power pack cooling system.

In the interest of evaluating emerging technologies, we have identified alternative cooling methods to augment, intensify, and enhance heat transfer in modern electrical equipment. These alternative cooling methods have already been used to achieve cooling of electrical components with varying success and include nucleate boiling, immersion cooling, heat pipes, and other augmentation techniques. If any of these alternative methods can be applied successfully to the generated electric drive concepts, there may be a significant prospect for further cooling system component/design streamlining. What these alternative methods are and how they influence the cooling system design of an electric drive system is the subject of this section.

The reference material that was used in the preparation of the following discussion are given at the end of section 5.7. In addition, the Applied Science and Technology Index and the Engineering Index were searched for articles from 1983 through 1986 to ensure the currentness of the effort.

Nucleate Boiling

Nucleate boiling generally refers to a heat transfer process that occurs along surfaces submerged in a fluid and is characterized by the formation of vapor bubbles. The formation of vapor bubbles usually indicates a very substantial heat flux. Reportedly, this heat flux is capable of supporting a surface cooling rate on the order of 100 W/CM^2 . In modern electronics cooling, several common fluorocarbon fluids may be used to take advantage of nucleate boiling to achieve temperature control. In particular, nucleate boiling provides the system designer with a potential means to cool those electrical components that may be difficult to supply with conventional oil or forced-air cooling.

This is because cooling can be designed into an electrical component by using the fluorocarbon fluid as a self-contained, nucleate boiling heat

sink. With proper design, recondensation of the fluorocarbon fluid can be achieved by thermal recycle through surface radiation and/or conduction. With this design, it is important to maintain the heat-sink surface in the nucleate boiling range and to avoid greater temperatures that would lead to a thermally unstable or less effective operation. Because of its self-contained and no moving parts feature, nucleate boiling merits further study as an alternative cooling technique for an electric drive system.

Immersion Cooling

Immersion cooling employs a liquid refrigerant to remove large amounts of generated heat and accomplishes this without the use of moving components that conventional cooling systems require. Similar to nucleate boiling in operation, immersion cooling relies on the evaporation of a refrigerant to maintain system temperature control. The vaporized refrigerant passes through a condensing operation where it gives up its latent heat of vaporization and runs back to a reservoir as a liquid under gravity.

Such a system has been developed and in use since the early 1970's for application in intercity passenger equipment, wayside substation equipment, and general industrial equipment. In particular, immersion cooling offers several advantages when many electrical elements are immersed in one tank and when the thermal load is cyclic. For example, these different elements may not necessarily carry their respective peak currents and hence heat load at the same time. The peak heat load for such a collection of elements will be less than the sum of the respective peak heat loads. In immersion cooling, it is possible to cool this collection of elements by having them share a common cooling surface. The size of this cooling surface will be based on the resulting peak load rather than the sum of the individual peak loads. Unlike immersion cooling, conventional cooling systems base their external cooling surface on individual peak loads. Hence, larger cooling surface sizes are more likely with conventional systems than with immersion cooling systems for equivalent heat removal. Moreover, the fluorocarbon liquid and reservoir of an immersion cooling system form a kind of thermal flywheel with a

thermal inertia. The thermal time constant for an immersion system can be on the order of 15 to 30 minutes compared to about 1 minute for the conventional air-cooling system. By using the fluorocarbon, the immersion system can be sized in terms of the average cyclic heat load, compared to the air-cooling system, which must be sized in terms of 1 minute average loads. For transportation application, this results in large weight and volume savings because the cooling system is no longer based on peak starting or operating loads.

Like the nucleate boiling system, the self-contained and no moving parts feature of immersion cooling merits further study as an alternative means for cooling electric drive components.

Heat Pipes

The heat pipe is a relatively recent development (1964) in heat transport devices. It is a self-contained heat pump that has the capability of transporting heat at a high rate with no external pumping power. The basic phenomena of evaporation, condensation, and surface tension pumping in a capillary wick permit the heat pipe to transfer latent heat continuously without the help of external work. Because it has a fraction of the weight and several hundred times the heat transfer capability of copper, silver, or aluminum, the heat pipe is ideally suited to conduct heat away from a surface by radiation, convection, or conduction. The components and principle of operation of a conventional heat pipe are shown in figure 5.7-16.

Use of the heat pipe in an electronic component cooling application most often dictates the heat pipe will operate in the moderate temperature range employing water, ammonia, Freon-21, or methanol as the working fluid. These fluids have normal boiling points that range from -10 to 216°F which are suited to cool electronic components operating in the 160-930°F surface temperature range.

With regard to electric drives, heat pipes have found application in the cooling of electronic modules, semiconductor devices, and induction

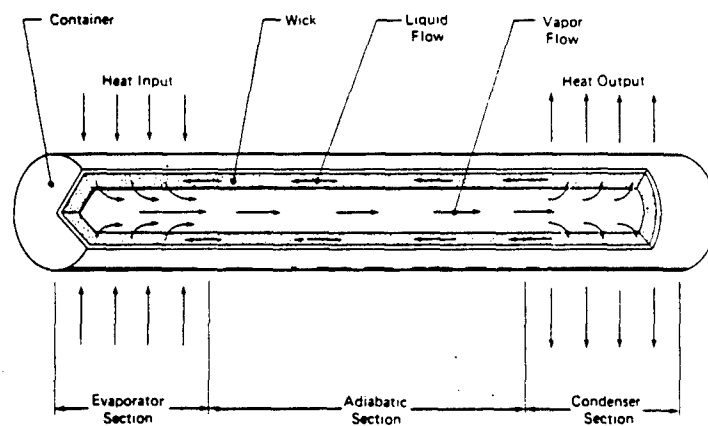


Figure 5.7-16. The Heat Pipe

motors. The performance data obtained lead to projections that heat pipes may handle heat dissipation rates 2.5 times higher than conventional water cooling and result in 25 percent savings of weight, as compared with air cooled machines. An additional advantage of heat pipes over conventional water/oil cooling is the elimination of sealing problems especially in the rotor and the transport of dissipated heat to locations where the heat can be removed easily and with low-cost measures.

Heat pipes possess heat transfer limitations which are governed by principles of fluid mechanics. The relative magnitudes of each of these limitations will depend on heat pipe geometry, working fluid, and wick characteristics. However, when the heat pipe is properly designed, it can be used to advantage. The demonstrated advantages of design simplicity, relatively low cost, silent operation, and long lifetime reliability suggest the heat pipe may be an innovative cooling solution in future electric drive technology.

Advances in Heat Exchanger Technology

Heat exchangers are a fundamental part of the conventional approach to cooling components of the electric drive system. They were used as the heat transfer surface to provide cooling for the concepts in this study. Because of their widespread acceptance, it is likely they will continue to be used in future electric drive programs. In recognition of this, advances in heat exchanger technology were identified for potential use in future electric drive systems. These advances were seen to take the forms of an extended range of operating conditions, a variety of additional materials including plastic, and significant improvements in manufacturing technology.

Shell and tube heat exchanger technology has advanced considerably in the past decade. The technology of integral finned tubing has improved to the point that exchangers are available in fin densities up to 40 fins/inch with fin heights from 0.03 to 0.06 inches, and tube outside diameters from 0.375 to 1 inch. Improved fin density associated with smaller tube diameters improves heat transfer surface area by several times over conven-

tional tubes. Wolverine Division of UOP has recently developed the Turbo-Chil finned tube which is an integral low finned tubing with internal enhancement. The Turbo-Chil enhanced tubing is reported to be prominent in the refrigeration industry in applications with condensation or vaporization outside the tubes and single phase fluid inside the tubes. Such an exchanger could be used to advantage in support of nucleate boiling or immersion cooling. Reportedly, other high performance tubings are GEWAT by Wieland-Werke AG of West Germany, Thermoexcel E by Hitachi Corporation of Japan, and High Flux Tubing by Union Carbide Corporation. In addition, Mitsubishi Electric Corporation of Japan has developed a unique plate fin exchanger made from hygroscopic paper. Used in ventilation air duty, the paper serves as a primary surface in combination with triangular fins made of special kraft papers. Although limited to a maximum operating temperature of 122°F, the attractiveness of paper, as a weight reducing measure, should be explored for limited application in future electric drive systems.

Plate fin exchanger technology has also experienced dramatic growth in recent years. Advances in manufacturing technology have produced high performance compact geometries. These geometries involve multilouver fins or offset strip fins. Granges Metalverken Company of Sweden has developed a highly compact multilouver copper fin with a fin density of about 50.5 fins/inch and corresponding heat transfer area density of 1341 ft.²/ft.³.

AiResearch has developed an aluminum offset strip fin that has a fin density of about 36.85 fins/inch and corresponding heat transfer surface area density of 1722 ft.²/ft.³.

In addition to design and manufacturing technology advancements, newly developed materials are also being emphasized in heat transfer applications. All plastic exchangers are available that promise weight reduction and improved corrosion resistance. In particular, Phillips Petroleum Company has developed a new material, Ryton PPS, which is being considered for plate heat exchangers because of its high strength and relatively inert properties. Ceramic is another material that has seen rapid development in heat exchanger application. Foam ceramic structure, with

its intrinsic small passages, provides a high surface area to volume ratio that has been used to advantage as an advanced gas turbinized recuperator. A ceramic counterflow recuperator for Stirling and gas turbine engines is under development by the Coors Porcelain Company.

Further Augmentation Techniques

Any technique that increases the heat transfer coefficient, h , or increases the heat transfer area, s , or increases both simultaneously may be considered an augmentation technique in a cooling system is to increase the heat flow or lower the permissible temperature difference or accomplish both of these simultaneously. It is thought that if these beneficial effects are achievable with augmentation, then the cooling system hardware sizing may be reduced and the overall system thermal effectiveness may be improved.

Basically, augmentation techniques are classified as active, passive, and compound. Active refers to those techniques that require power while passive techniques do not and compound encompasses techniques from both passive and active categories.

Passive Techniques

Following is a brief description of some of the more common passive augmentation techniques encountered in the literature:

- o Treated Surfaces
- o Rough Surfaces
- o Extended Surfaces
- o Displaced Enhancement Devices
- o Swirl Flow Devices
- o Surface Tension Devices
- o Additives for Liquids
- o Additives for Gases

The literature reports that a treated surface can be an effective technique for augmentation of boiling heat transfer to fluorocarbons. One example given is the brazed coating marketed commercially as High Flux. The purposeful dendriting or crazing of a surface has also been used with success. It is believed that chip carrying substrates or transistor surfaces may be modified as a striated surface to enhance heat transfer.

Surface roughness has long been considered a means of augmenting heat transfer in the forced-convection mode. However, this technique is usually associated with increased pumping cost that represents a trade-off.

Vortex generators, such as static mixing devices, have long been known to promote mixing and improved heat transfer rate. In one study, use of this device improved the heat transfer coefficient by as much as 100 percent. The benefit of improved heat transfer coefficient must be weighed against the increased pumping cost resulting from the increased turbulence.

As a surface tension device, wicking has been used whenever there is an unreliable supply of liquid to a heated surface in a critical application. Wicking (which includes heat pipes) have been considered for thermal control in a number of electronic applications. As they need an intimate contact with the surface to be cooled, wicking is sometimes used in conjunction with enhanced surfaces.

Working Fluids

The working fluid for a heat transfer system is normally specified by the process or chosen on the basis of its desirable properties. The purpose of a liquid additive is to preserve the desirable properties of the working fluid while still improving the heat transfer. A great many additives have been investigated and some have been found to produce substantial improvements in heat transfer. In saturated nucleate boiling, liquid additives were determined to raise the heat transfer coefficient by 20 to 40 percent. Liquid additives remain a viable technology for investigation of nucleate boiling and/or immersion cooling are considered in future cooling system designs.

Active Techniques

Following is a brief description of some of the more common active augmentation techniques encountered in the literature:

- o Mechanical Aids
- o Surface Vibration
- o Fluid Vibration
- o Electrostatic or Magnetic Fields
- o Injection and Suction

Mechanical aids for the transfer involve stirring the fluid by mechanical means or by rotating the surface across which the transfer must occur. The literature shows mixed results for these techniques. In one experiment, surface scraping was seen to be an effective approach for increasing the forced convection heat transfer. However, it was concluded that the necessary hardware is usually not compatible with most available heat exchangers.

Surface vibration and fluid vibration have also been used to increase the heat transfer coefficient in the cooling of electronic equipment. In comparing these techniques, it was found that fluid vibration was the more practical augmentation technique due to the mass of most heat exchangers. The vibrations used typically range from about 1Hz to ultrasound. Some workers have questioned the efficiency of this approach when system reliability is also taken into account. Again, mixed results are reported in the literature for each type of vibration. In general, it can be said that vibration is not effective as an augmentation technique to warrant the rather cumbersome equipment normally associated with its use.

Electrostatic fields (AC or DC) have been tested in small scale experiments as a technique to improve heat transfer. To be successful, this technique must be used with a dielectric fluid and directed in a manner to cause greater bulk mixing of the fluid in the vicinity of the heat transfer surface. In one experiment, a voltage in the 10kv range was observed to produce an improvement in heat transfer rate on the order of 100 per-

cent. Such conditions may often be encountered and taken advantage of in a power transformer. Electrostatic fields may offer potential for augmentation in cooling of electronic equipment if it can be tolerated and is practical without energy consumption penalty.

Injection involves the forced supply of gas into a flowing liquid through a porous heat transfer surface. It is believed that the resultant bubbling produces a beneficial effect on the heat transfer rate similar to nucleate boiling. Suction relates to vapor generation and removal through a porous heated surface as might be experienced in nucleate boiling. Some experimentation has shown it was possible to increase the heat transfer coefficient by as much as 150 percent under certain conditions.

To summarize, the equipment usually associated with active augmentation is relatively expensive and complex to operate. A further consideration is that its use may act to reduce the overall reliability of the equipment being cooled.

5.7.2 Future System Improvements

Predictions of future electric drive system improvements were made based on the component technology future trends of the previous section, the current and near term electric drive systems from phase II of the electric drive study contract, and past electric machinery experience. Critical technologies, those that are projected to have the most impact on future electric drive systems, are also identified.

The best electric drive concepts determined in phase II of the electric drive study were analyzed to determine the weight and volume contribution of the subsystems that make up the total system. This analysis is useful in that generally subsystems with large weight and volume contributions have high potential for producing significant system improvement if component technologies associated with these subsystems indicate major future improvements. Conversely, subsystems that contribute minimally to the total system generally will not generate significant system improvements.

The weight and volume contribution of six major subsystems/subdivisions to total installed transmission weight and volume are presented in figures 5.7-17 and 5.7-18 for the best electric transmission concepts from the phase II effort and for two hydrokinetic transmissions (DDA X300 and DDA ATT1064). The six subsystems/subdivisions considered include traction motors, power electronics, gears, cooling, generator, and miscellaneous. The installed weights and volumes presented in figures 5.7-17 and 5.7-18 are for transmission only and do not include final drives, engine, and engine subsystems. Power to weight and power to volume ratio values are given in figures 5.1-17 and 5.7-18 for the transmission presented.

The weight information of figure 5.7-17 shows for the 19.5 ton DC system (by ACEC) that the traction motor along account for 65 percent of the system installed weight and is the dominant contributor. Regarding AC transmission systems for both 19.5 and 40.0 ton vehicle applications, the traction motors, power electronics, gears, and cooling have significant impact on system weight.

Concerning the volume information of figure 5.7-18 the DC motors again have a major impact on the total installed system volume for the 19.5 ton vehicle application with conventional DC drive. Although the gears and cooling system also contribute significantly to total volume. For 19.5 and 40.0 ton vehicles with AC electric transmissions the power electronics, cooling, and gears have the most dominant contribution to system volume.

5.7.2.1 Critical Technologies

Two critical technology areas were identified from the technology trends and the weight and volume analysis of the best electric transmission concepts. These critical technologies are power semiconductors and permanent magnetic materials. The permanent magnet technology growth will significantly impact the weight and volume of traction motors and the projected improvements in power semiconductors will reduce the volume of power electronics dramatically.

A third critical technology is current collection brushes for homopolar machinery applications. Future improvements in brush speed and in current density are projected to result in significant reduction of homopolar drive

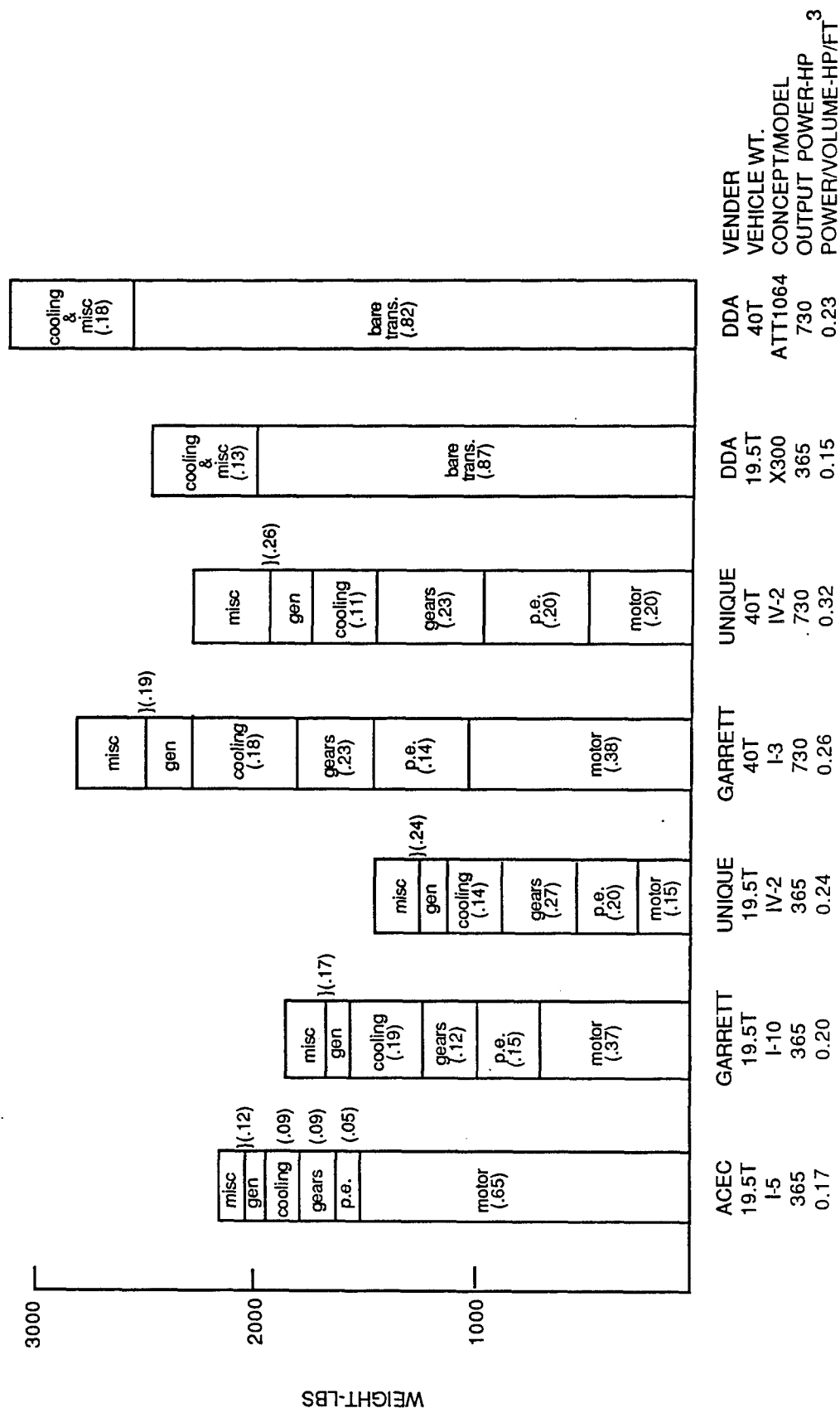


Figure 5.7-17. Weight Comparison for Best Electric Transmission Concepts

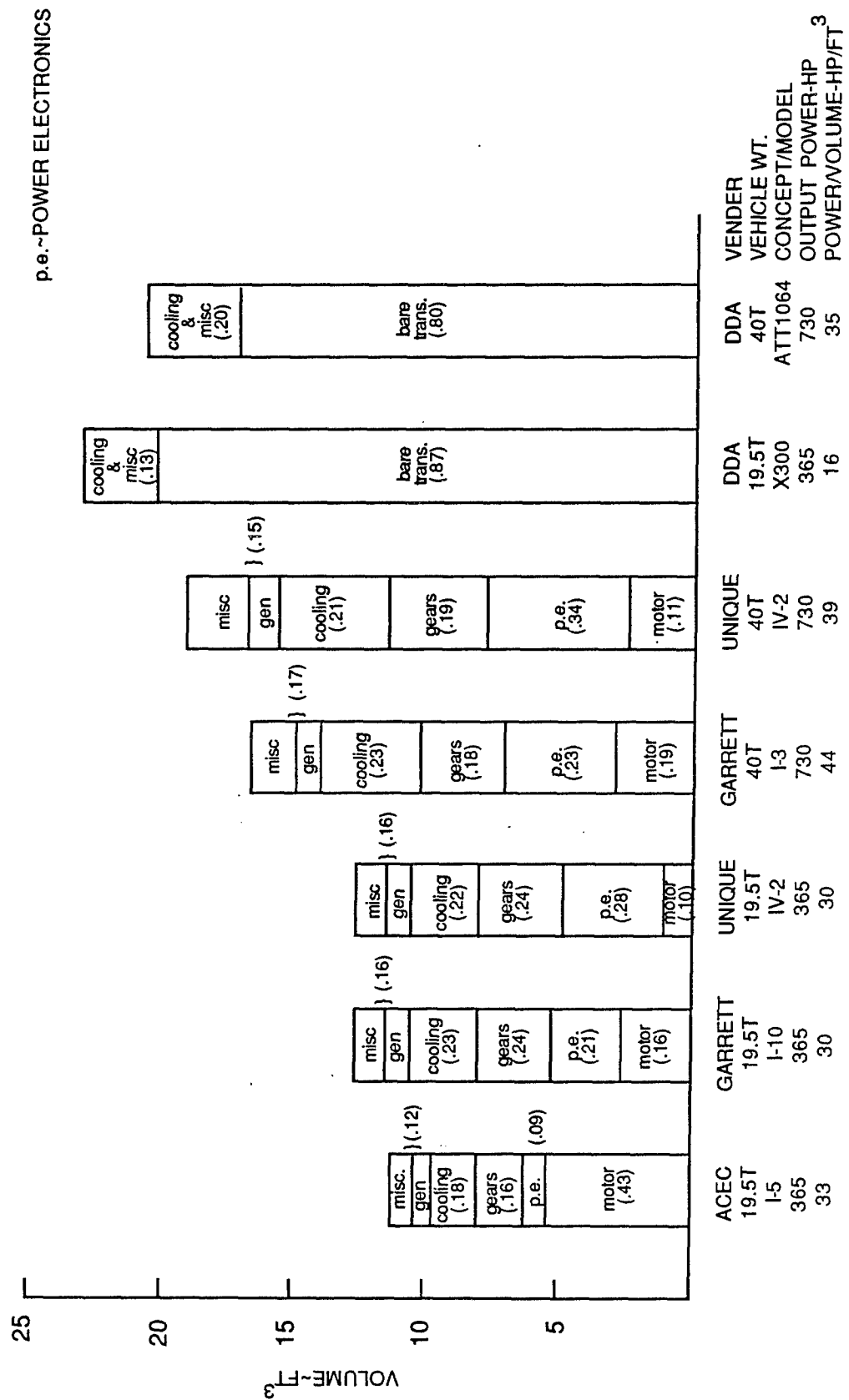


Figure 5.7-18. Volume Comparison For Best Electric Transmission Concepts

weight which has been a major disadvantage of this system. Homopolar drives are attractive for heavy combat vehicles due to their relative simplicity. One aspect of this simplicity is that no power electronics are required in the main power circuit resulting in significant reduction of the rating and physical properties of the electronics.

Although not considered a critical technology area, improved cooling techniques and optimization of integrated cooling systems offers some meaningful improvements in electric machinery size and weight and in cooling system physical characteristics.

It is also worth noting that improvements in DC motor design could payoff in significant improvement for DC drive systems. However, no significant development activities in technologies that would produce these improvements were identified by this study.

5.7.2.2 Electric Machinery Projections

This section addresses growth projections for the major electric machinery used in electric transmissions including alternators, traction motors, and power conditioner units. The growth projections are developed based on the following sources:

- o Past electric machinery data
- o Near term electric machinery data from the electric drive study (considered as in production by 1990)
- o Technology trends from the parametric study

Trends of power/weight and power/volume for alternators, AC traction motors, and power conditioner units are presented in figures 5.7-19, 5.7-20, and 5.7-21. The trends are generally based on past and present production designs from 1975 to 1987 and on production design projection out to 1995.

The alternator trends of figure 5.7-19 show improvement in weight and volume of over 15 percent from 1990 to 1995 production. This growth is based on improvements in permanent magnet materials and cooling techniques. The

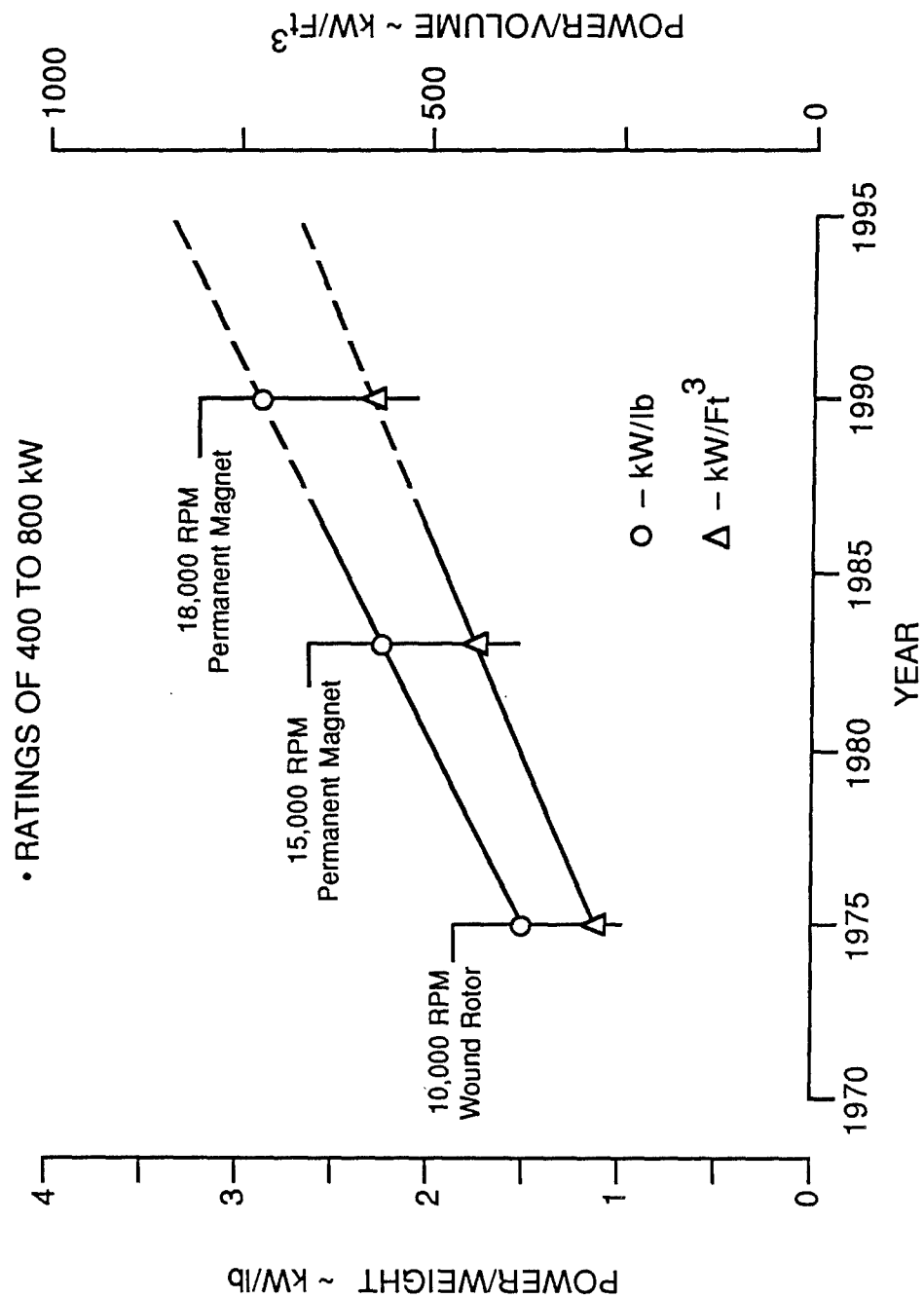


Figure 5.7-19. Alternator Trends

projection from 1990 to 1995 assumes that maximum rated speed remains at 18000 rpm. If max speed can be increased through improved design then greater improvements than shown is possible.

AC permanent magnet traction motor trends are given in figure 5.7-20 and indicate improvements of approximately 20 percent for both weight and volume from 1990 to 1995 production. The improvement is due to the use of permanent magnet materials with greater energy product, improved electromagnetic design, and advanced cooling. The trends of figure 5.7-20 are predicated on motor designs with a rated power speed range near 4 to 1 and short time duty rating of 3 times continuous.

Trends for power conditioner units are presented in figure 5.7-21 and indicate over 20 percent improvement in weight and volume from 1990 to 1995. This improvement is based primarily on power semiconductor growth and is somewhat conservative based on the potential growth of controls indicated in section 5.7.1.5. The power conditioner trends are based on units with rating of 200 to 400 kilowatts and short duty ratings of three times the continuous rating. The power conditioner units incorporate a rectifier and inverter with a DC link. The 1990 power conditioner unit (PCU) is based on transistor or GTO technology and the 1995 PCU is based on MOS controlled thyristor technology.

5.7.2.3 Future Electric Transmission Improvements

Projections of future electric transmission installed weight and volume characteristics were developed from the best concepts of phase II and the electric machinery projections of the previous section. The best electric transmission systems from phase II are considered as fully developed and in production by 1990. The electric machinery improvements from the previous section were applied to the 1990 production system to produce systems that are considered probable for 1995 production. Table 5.7-2 presents the resulting power to weight values for the 1990 and 1995 production versions of the best electric transmissions for 19.5 and 40.0 ton vehicles. Table 5.7-3 presents the power to volume values in a similar manner. The improvement of the 1995 systems relative to the 1990 systems is also tabulated in these tables. The Garrett AC permanent magnet drive shows the greatest improvement with 15

- MAX SPEED 18000 RPM
- INTERMITTENT DUTY 3X RATED
- RATED POWER SPEED RANGE 4 TO 1

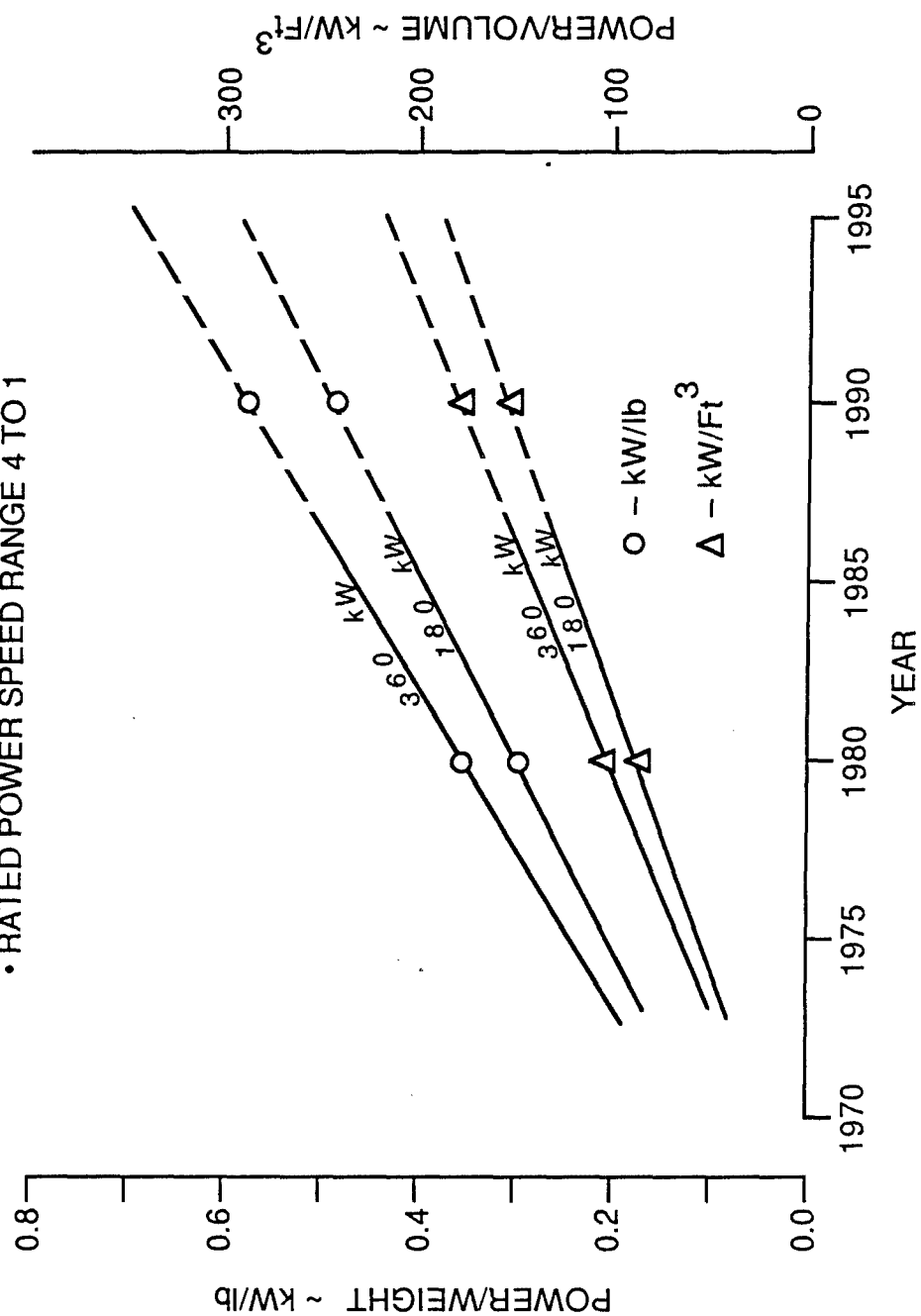


Figure 5.7-20. AC Traction Motor Trends

- RATINGS OF 200 TO 400 kW
- INTERMITTENT DUTY 3X RATED

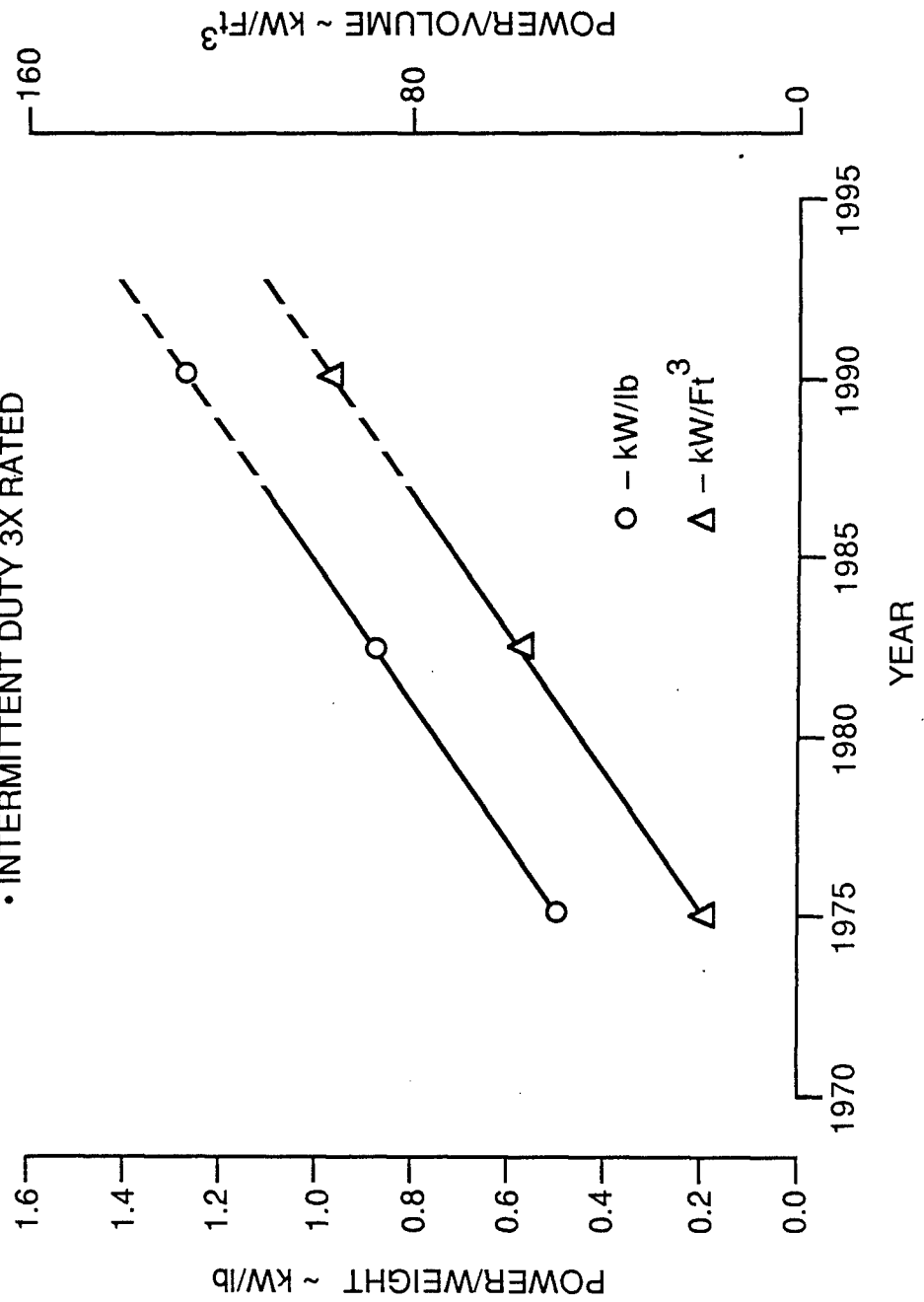


Figure 5.7-21. Power Conditioning Unit Trends

percent or more in both vehicle weight categories. The ACEC conventional DC system for the 19.5 ton vehicle application indicates the least improvement with 6 percent. Comparable weight and volume characteristics for the DDA X 300 and ATT1064 hydrokinetic transmissions are also included in the tables for comparison. Transmission weight and volume characteristics given in tables 5.7-2 and 5.7-3 incorporate the transmission cooling but do not include the final drives.

Table 5.7-2. Future Electric Transmission Power/Weight Improvement

Vehicle Weight/ Transmission Description	1990 Production Power/Weight ¹ (HP/LB)	1995 Production Power/Weight ¹ (HP/LB)	Improvement (Percent)
<u>19.5 Ton Vehicle</u>			
ACEC DC Trans.	0.17	0.18	6
Garrett AC PM Trans.	0.20	0.23	15
Unique AC PM Trans (Dual Path)	0.24	0.26	8
DDA X 300 Trans.	0.15	-	-
<u>40.0 Ton Vehicle</u>			
Garrett AC PM Trans.	0.26	0.30	15
Unique AC PM Trans. (Dual Path)	0.32	0.35	9
DDA ATT1064 Trans	-	0.23	-

Note 1 Power at sprocket/installed weight

Table 5.7-3. Future Electric Transmission Power/Volume Improvement

Vehicle Weight/ Transmission Description	1990 Production Power/Volume ¹ (HP/LB)	1995 Production Power/Volume ¹ (HP/LB)	Improvement (Percent)
<u>19.5 Ton Vehicle</u>			
ACEC DC Trans.	33	35	6
Garrett AC PM Trans.	30	35	16
Unique AC PM Trans (Dual Path)	30	34	13
DDA X 300 Trans.	16	-	-
<u>40.0 Ton Vehicle</u>			
Garrett AC PM Trans.	44	51	16
Unique AC PM Trans. (Dual Path)	39	44	13
DDA ATT1064 Trans	-	35	-

Note 1 Power at sprocket/installed volume

The last discussion in this section addresses the design of a DC homopolar transmission system for a 40.0 ton combat vehicle. This discussion is presented to update DC homopolar drives due to recent advances in current collection systems that will allow significant increases in current density and surface speed and potentially produce significant system weight and volume reduction.

5.7.2.3.1 DC Homopolar Drum Machine, Design and Performance

We assume the balanced drum structure shown in figure 5.7-22. We are given, as specified values, the air gap power P_o , the drum speed voltage V_s , and the brush linear velocity V_b . The air gap field flux density at the drum outer radius R_o is chosen to be B_o , and we require that this density be maintained at the end faces of the drum. The drum outer surface is enclosed by a copper sleeve of radial thickness DR_{si} . The armature current at current density J_c is induced in and flows through this sleeve conductor. To prevent armature reaction an outer sleeve of radial thickness ΔR_{s0} conducts the armature current, anti-parallel to the drum current, to the armature current terminals located at the machine center. The active axial length of the drum is $2L_a$. Over this length the field flux is in space quadrature with the inner sleeve circumferential movement and the inner sleeve axial current flow. At the two end regions of the drum, brush structures of axial length L_b collect the inner sleeve current and transfer it to the outer sleeve conductor. These brushes cover a fraction F_b of the available brush area ($2\pi R_o L_b$) and have a brush current density of J_b .

The entire drum is embedded in the field iron outer shell. The outer radius of the shell is R_{shell} and the allowed field flux density is specified as B_{shell} . The field coils, assumed square, have a side length of L_c , a packaging factor of F_c and a current density within the field copper of J_c .

The total field flux ϕ_f for one field coil can be evaluated at the outer radius of the drum as

$$\phi_f = 2\pi R_o L_a B_o \quad . \quad (H1)$$

This flux passes a given point on the outer surface of the drum at a rate of $V_b/(2 R_o)$ times a second. Thus the total drum induced speed voltage is given by

$$V_s = 2 \times \frac{V_b}{2\pi R_o} \times 2\pi R_o L_a B_o \quad . \quad (H2)$$

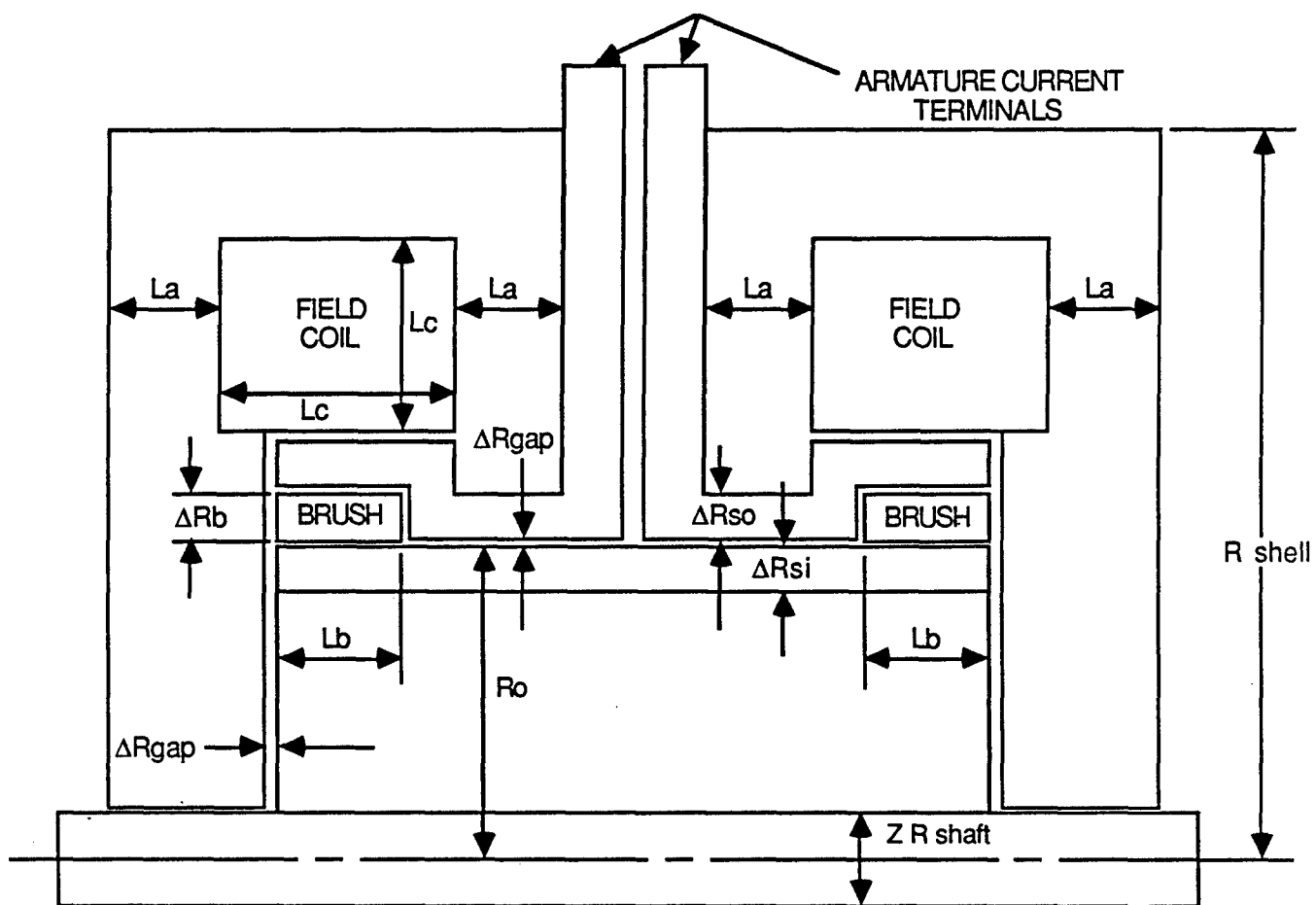


Figure 5.7-22. Diagram of Homopolar Machines

So the required drum axial length per field coil is given by

$$L_a = \frac{V_s}{2 v_b B_o} \quad (H3)$$

Since we require the field flux to flow through equal cross-sectional areas of drum iron, not including the shaft, we must have

$$2 \pi R_o L_a = \pi [(R_o - R_{si})^2 - R_{shaft}^2] \quad (H4)$$

The difference $R_o - R_{si}$ can be expressed as a function of the needed sleeve cross sectional area A_s (needed to carry armature current $I_o = J_c A_s = P_o/V_s$) and the drum radius R_o since

$$A_s = \pi [R_o^2 - (R_o - R_{si})^2]$$

we have

$$(R_o - R_{si})^2 = R_o^2 - A_s/\pi \quad (H5)$$

If we substitute this into (H4) we obtain an equation for the drum radius

$$R_o^2 = 2 L_a R_o - (A_s/\pi + R_{shaft}^2) = 0$$

Which can be solved for R_o as

$$R_o = L_a + \sqrt{L_a^2 + A_s/\pi + R_{shaft}^2} \quad (H6)$$

Where the sleeve area A_s is given by

$$A_s = \frac{I_o}{J_c} = \frac{P_o}{J_c V_s}$$

and L_a is given by (H3).

Now from (H5)

$$\Delta R_{si} = R_o - \sqrt{R_o^2 - A_s/\pi} \quad (H7)$$

and from a similar development for the outer sleeve

$$\Delta R_{so} = \sqrt{R_{gap} + A_s/\pi} - R_{gap}, \quad (H8)$$

where $R_{gap} = R_o + \Delta R_{gap}$ and ΔR_{gap} is the air gap radial thickness.

From the gap power equation

$$P_o = V_s I_o = V_s 2\pi R_o L_b F_b J_b$$

we have

$$L_b = \frac{I_o}{2\pi R_o F_b L_b} \quad (H9)$$

If the brush material has a radial length of ΔR_b and a bulk resistivity of ρ_b the brush resistance R_b , per side, is given by

$$R_b = \frac{\rho_b \Delta R_b}{2\pi R_o F_b L_b}$$

If each brush has a contact drop of V_{ct} , the equivalent contact resistance R_{ct} at rated current I_o is then given by

$$R_{ct} = \frac{V_{ct}}{I_o}$$

The total resistance of the sleeves R_s , for copper resistivity ρ_c is given by

$$R_s = \frac{4\rho_c (l_a + L_b)}{A_s}$$

The total armature resistance R_{arm} is then given by

$$R_{arm} = R_s + 2 (R_b + R_{ct}) \quad (H10)$$

If we assume that the total field mmf is dropped across the air-copper gaps we have for the total field flux gap, L_f

$$L_f = R_{si} + R_{so} + 2 \pi R_{gap} \quad (H11)$$

where we have assumed that the drum end air gap is the same length as the drum radial air gap. The field flux path reluctance is then given approximately by

$$R_f = \frac{L_f}{\mu_o 2 \pi R_o L_a} \quad (H12)$$

where μ_o is the magnetic permeability of free space. And the required field coil ampere turns is

$$I_f N_f = \frac{B_o 2 \pi R_o L_a}{R_f} \quad (H13)$$

For an assumed square field coil structure of side length L_c we have

$$L_c = \sqrt{\frac{I_f N_f}{F_c J_c}} \quad (H14)$$

If the mean length of a field coil turn is given by $2 \pi (R_{gap} + \Delta R_{so} + L_c/2)$ the total field coil resistance R_c is

$$R_c = \frac{F_c 2 \pi (R_{gap} + \Delta R_{so} + L_c/2)}{F_c L_c^2} \quad (H15)$$

and the field coil $I^2 R$ loss is given by

$$\text{field } I^2 R = (I_f N_f)^2 R_c \quad (H16)$$

The outer radius of the field coil Recoil is

$$R_{coil} = R_{gap} + \Delta R_{so} + L_c \quad (H17)$$

and the outer radius of the total machine, R_{shell} is

$$R_{shell} = \sqrt{\frac{\phi f}{B_s} + R_{coil}^2} \quad (H18)$$

The total machine length L_m is

$$L_m = 2 (2 L_a + L_c - \Delta R_{so}) \quad (H19)$$

and the total machine volume Vol is approximately

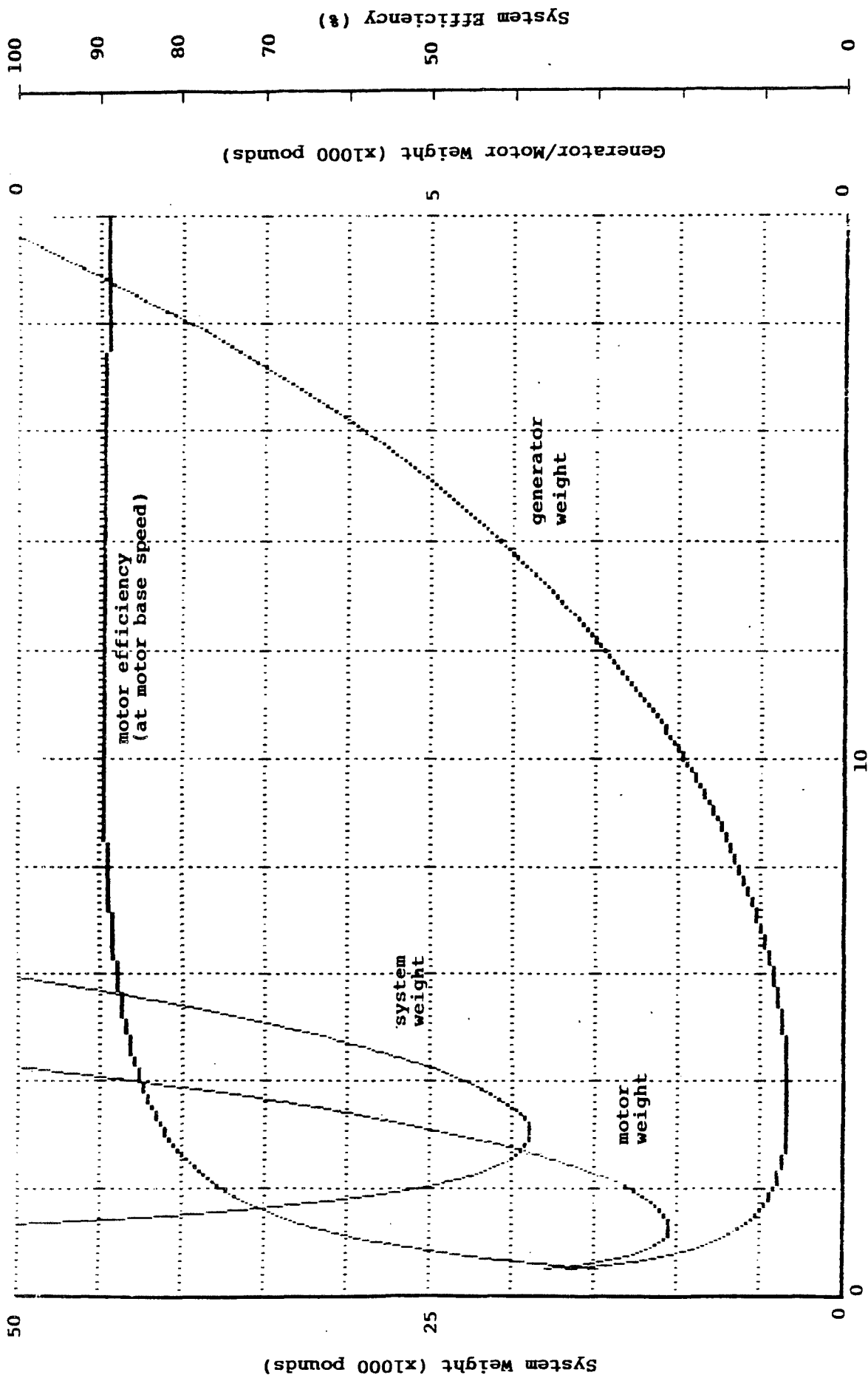
$$Vol = R_{shell}^2 L_m \quad (H20)$$

If we assume this entire volume is filled with iron we will then have a conservative estimate of the machine mass.

The only remaining loss mechanism needed to calculate the machine efficiency, is the brush friction loss. If the coefficient of sliding friction of the brush material is μ_b and the mean brush pressure is P_b we have for each brush

$$\text{friction loss} = \mu_b \times p_b \times 2\pi R_o F_b L_b \times v_b \quad (H21)$$

A computer program has been written to evaluate the above design performance equations. Several output plots from the program are given in figure 5.7-23 through 5.7-26. In these figures example results for component weights and system efficiency are given for DC homopolar machine designed for the 40-ton vehicle considered in this study as a function of specified motor speed voltage. The traction motors air gap (output) power rating is assumed to be 400 hp and the air gap (input) power rating of the generator is assumed to be 900 hp. Values of the different constants needed to evaluate equation (H1) through (H21) are given in table 5.7-4. The bus conductors for the generator - two motor systems of figures 5.7-23 through 4.7-26 are assumed to be 4 meter



System Weight (x1000 pounds)

Figure 5.7-23. Homopolar System Characteristics

Motor Speed Voltage (volts)

motor brush velocity: $v_b = 100/10$ m./s.
generator brush velocity: $v_b = 100$ m./s.

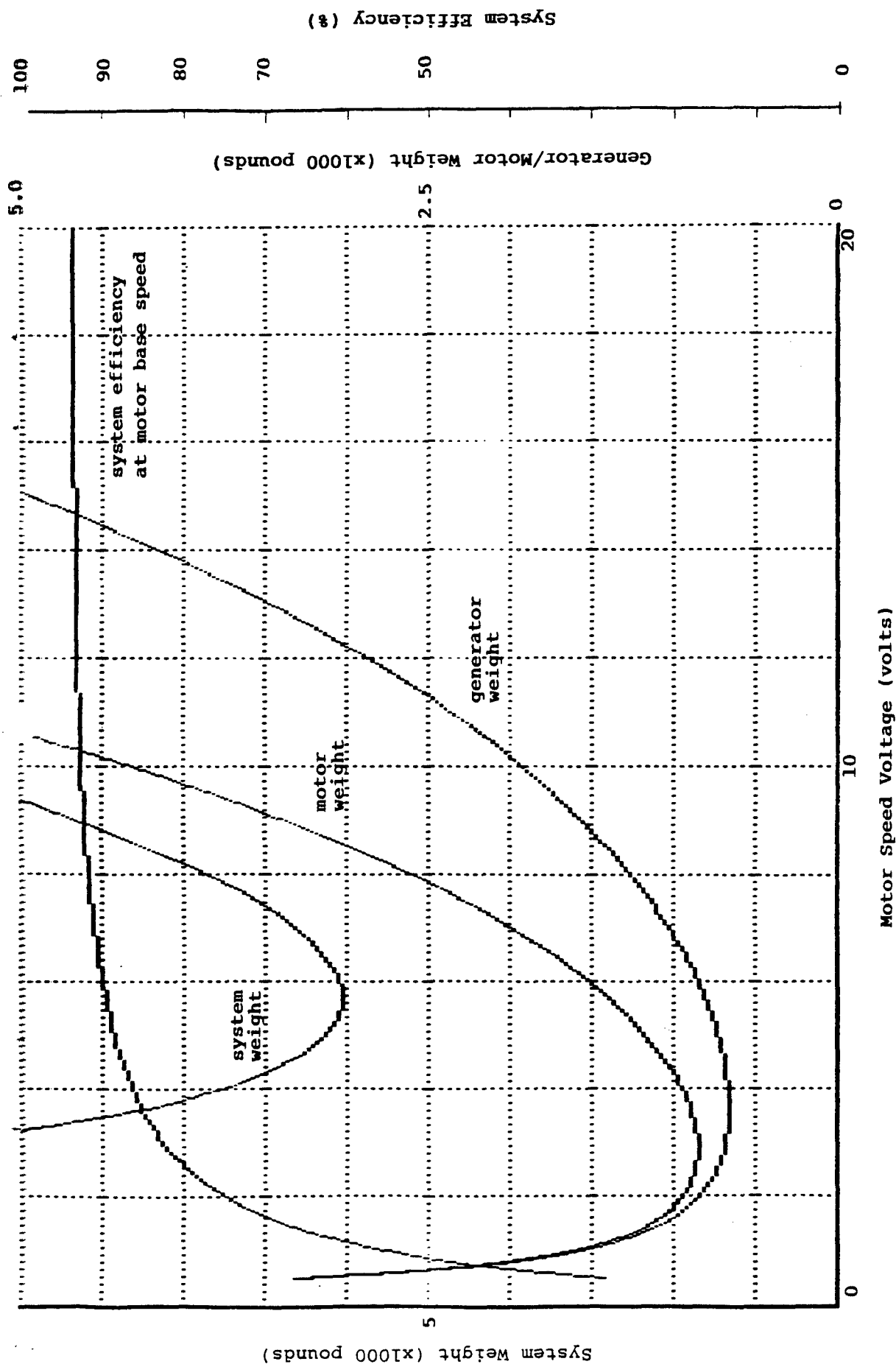
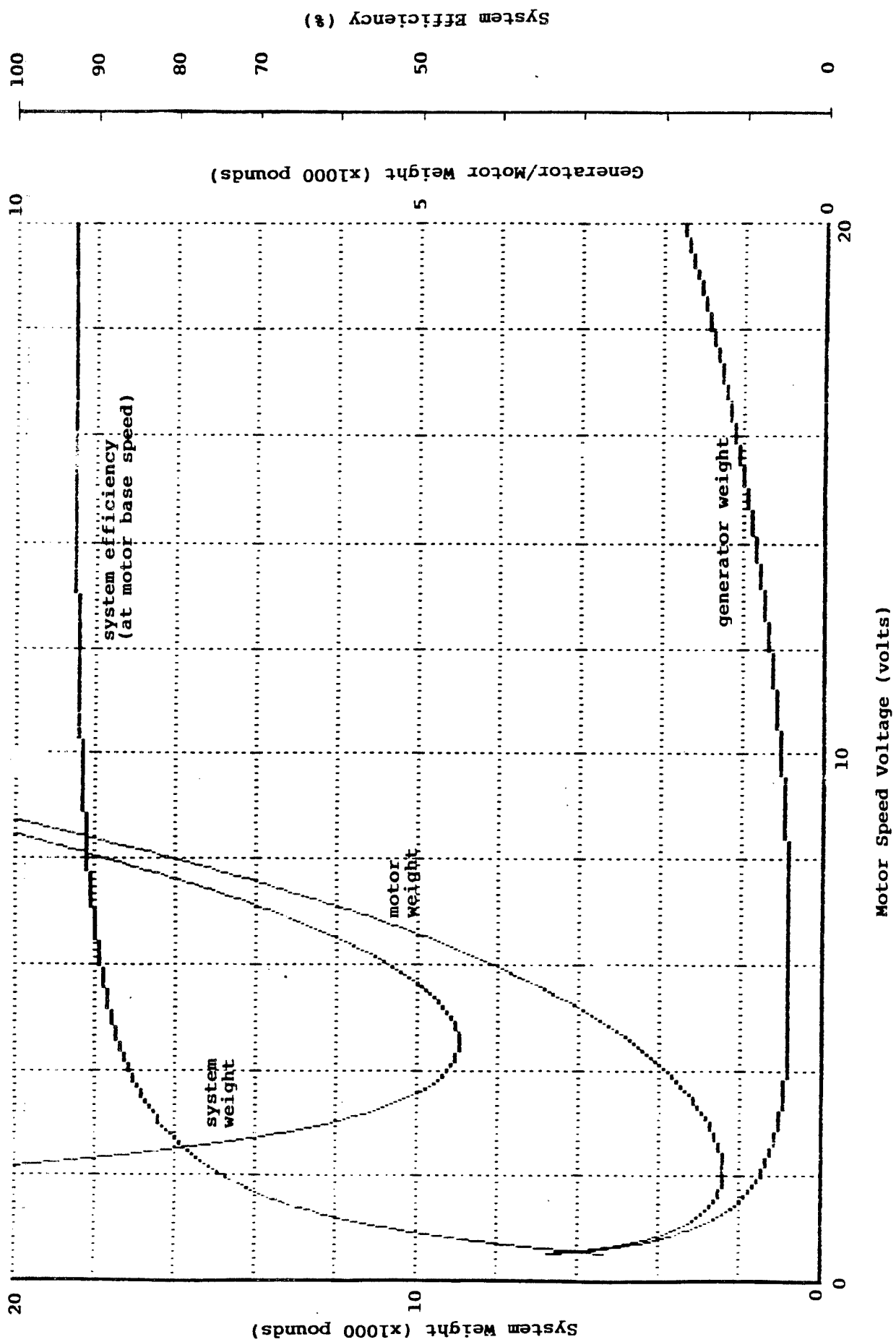


Figure 5.7-24. Homopolar System Characteristics



motor brush velocity: $v_b = 200/10$ m./s.
generator brush velocity: $v_b = 200$ m./s.

Figure 5.7-25. Homopolar System Characteristics

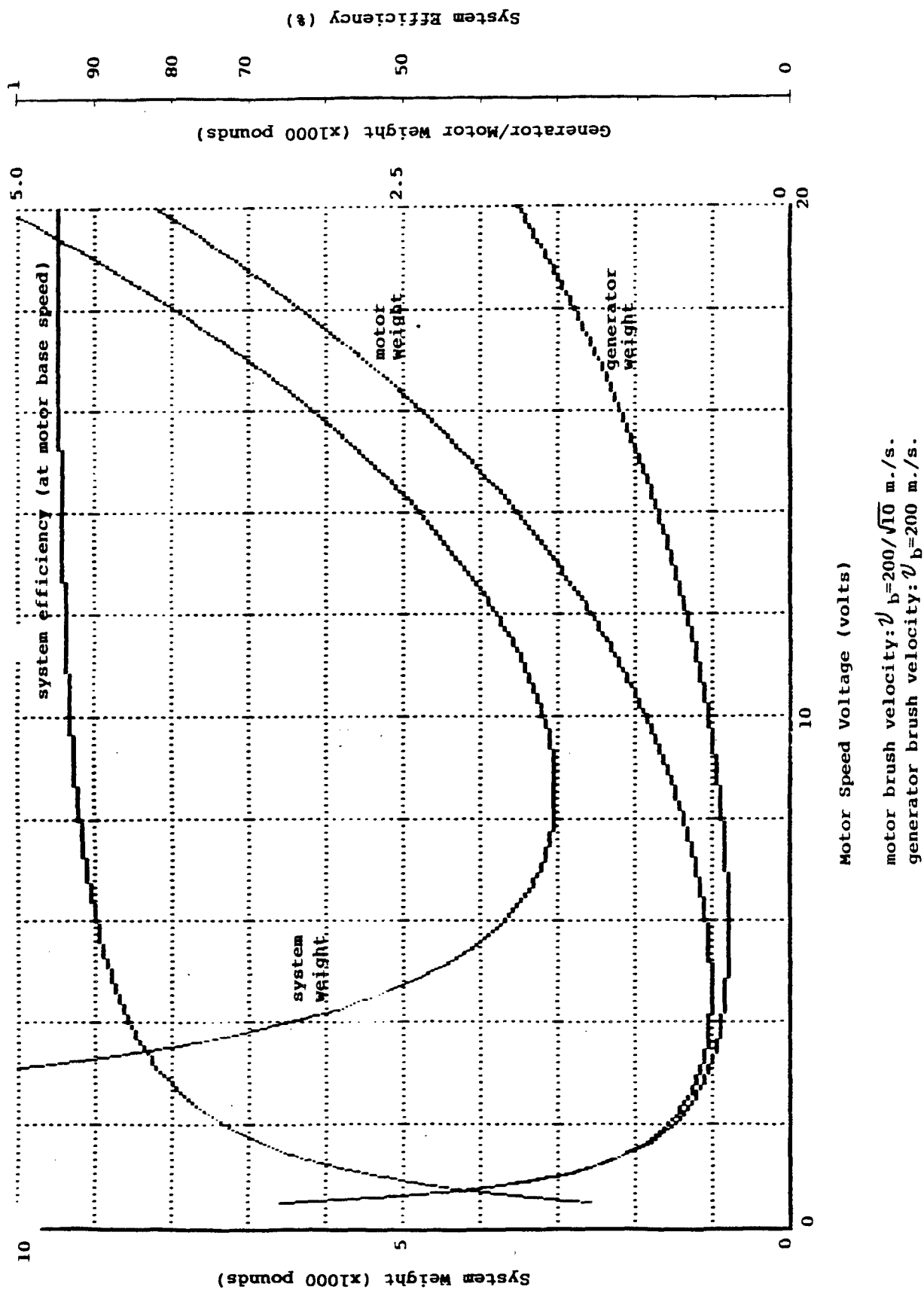


Figure 5.7-26. Homopolar System Characteristics

lengths of copper conductor. The cross-sectional area of the busses are fixed at values such that the bus I^2R loss will be 8 hp at rated armature current (or 1 percent of the rated output for both motors). The system efficiency is calculated on the assumption of full motor output at all values of specified motor speed voltage.

The values for maximum brush velocity in the examples of figures 5.7-23 through 5.7-26 are 100 and 200 meters per second and the value of brush current density of 10^7 amperes per square meter are both taken from recent work in the SDI program. In fact, a current WPAFB effort is to demonstrate steady-state brush current densities of 2×10^7 amperes per square meter at 200 meters per second sliding velocity. The results shown in figures 5.7-23 thru 5.7-26 indicate the clear advantage of higher sliding velocities and the rather severe weight penalty which must be paid for traction motor design with a 10 to 1 constant power output speed range. Motor design which drive two speed reducing gear boxes need only a $\sqrt{10}$ to 1 constant power speed range and are much lighter.

TABLE 5.7-4
CONSTANTS USED IN THE DC HOMOPOLAR MACHINE
DESIGN AND ANALYSIS

Shaft radius	Rshaft	0.0381 m	
Brush radial thickness	ΔR_b	0.01 m	
Air gap thickness	ΔR_{gap}	0.0025 m	
Air gap field flux density	B _o	1.3 T	
Shell field flux density	B _{shell}	1.5T	
Brush coefficient of sliding friction	μ_b	0.2	
Brush pressure	p _b	10 ⁴ N/M ²	
Brush contact drop	V _{ct}	0.1 V	
Copper maximum current density	J _c	10 ⁷ A/M ²	
Brush maximum current density	J _b	10 ⁷ A/M ²	
Average machine density	ρ_m	7800 kg/m ³	
Copper resistivity	ρ_c	1.7 x 10 ⁻⁸	m Ω
Brush resistivity	ρ_b	3.4 x 10 ⁻⁸	m Ω
Brush coverage fraction	F _b	0.5	
Field coil fill fraction	F _c	0.6	

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APPENDIX A

19.5 and 40.0 Ton Vehicle Specifications

19.5 Ton Vehicle Specifications

1. General Vehicle Specifications:

Frontal Area	5.3 sq m (57 ft ²)
Gross Vehicle Weight	17.6 ton (<u>19.5 ton</u>)
Vehicle Top Speed (Governed)	73 Km/hr (45 mph)
Track Length (forward to aft roadwheel centerline)	3810 mm (150.0 in)
Distance between track (longitudinal centerline)	2350 mm (92.52 in)
Track Width	445 mm (17.52 in)

2. Propulsion System Specifications:

a. Transmission: (Electric Drive System)

The drive system shall provide automatic speed ratio control and inhibitors to prevent engine overspeed. Maximum output torque required shall be sufficient to generate a tractive effort of 208,000 Newtons, Reverse - 208,000 Newtons. There shall be tactile feedback to the driver when the transmission is in forward or reverse operational mode. The power train shall provide for safe, predictable performance for extended periods at speeds below 5 Km/hr.

b. Steer System:

A regenerative speed control system is required. Differential torque between sides shall be equal to maximum steer torque. Pivot steer capability on hard surface shall be 7 revolutions/min. The steering controls shall remain operative in the event of engine failure or vehicle towing. The steer system shall be capable of accepting full engine power.

c. Cooling Capability:

Capable of continuous tractive effort operation of at least 121,500 N.

d. Braking:

The vehicle shall be capable of a deceleration rate from maximum speed on level hard surface road at least 7 m/sec^2 (peak and 5 m/sec^2 (avg.)). The vehicle shall be capable of an included hold with engine off on at least a 60% slope. The vehicle shall be capable of at least 25 stops from 60 Km/hr @ 5 m/sec^2 @ 3 minute intervals. The braking functions shall be accomplished by two separate mechanisms to allow redundancy for emergency purposes.

3. Electric/Hydraulic Power Capability:

Continuous operation of all vehicle electrical and hydraulic systems shall be at least 7 Kw, to include silent watch - the silent watch is non-mobile, with noise, light, and smoke discipline. The above power requirement covers turret hydraulic, radio, and other electrical needs, compartment ventilation and NBC countermeasure equipment. Electrical and hydraulic power sources must be capable of operating independently or in parallel in a stable self regulating manner. Average auxiliary power usage is 2.5 Kw.

f. Speed on Grade:

The propulsion system shall be capable of sustaining forward vehicles speeds on hard surface roads and grades as defined in figure A-1.

g. Acceleration:

The vehicle shall be capable of acceleration on dry level surface from idle, from application of the throttle, in the forward direction from zero to 32.2 Km/hr (20 mph) in seven seconds; and in reverse direction from zero to 16 Km/hr (10 mph), in five seconds. Assume no "throttle" linkage delay.

h. Engine: See figure A-2.

i. Shock:

The electric drive system must be able to withstand a 15 g shock and in any direction.

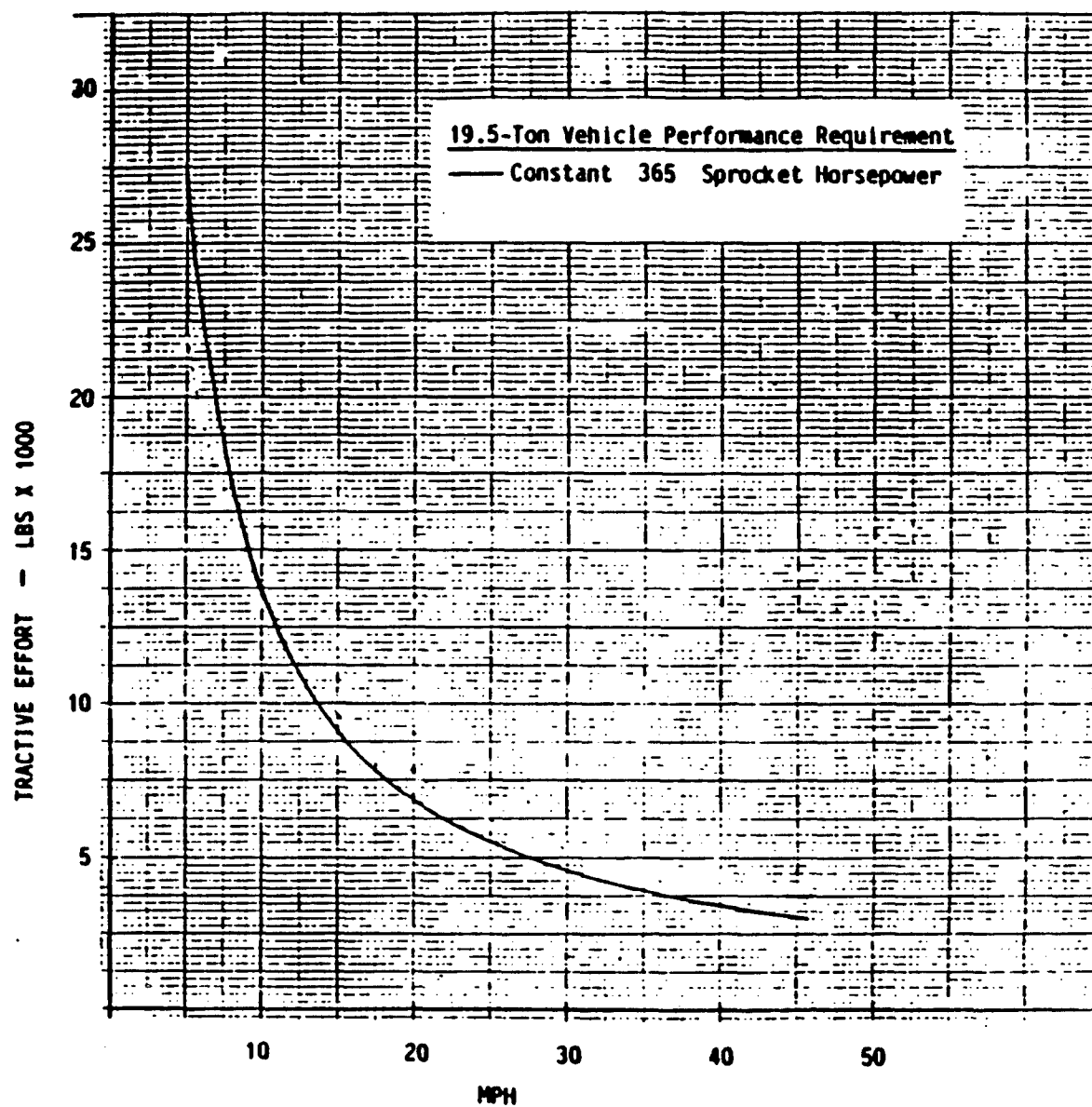


Figure A-1. Tractive Effort Versus Vehicle Speed.

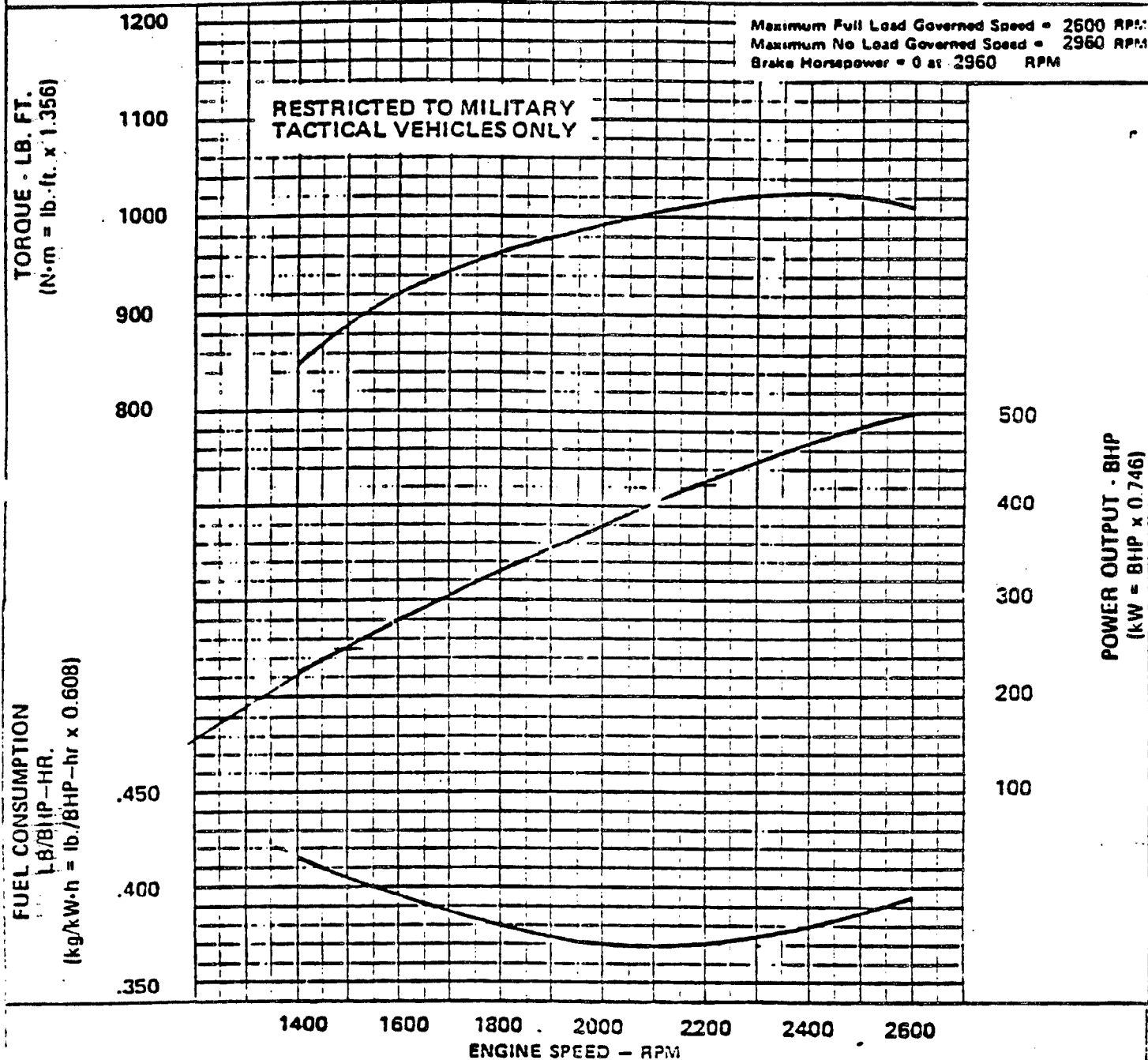


CUMMINS ENGINE COMPANY, INC.
Columbus, Indiana 47201
AUTOMOTIVE PERFORMANCE CURVE

BASIC ENGINE MODEL:
VTA-903-T
ENGINE FAMILY:
CPL CODE:
0383

CURVE NUMBER:
RC-3914-A
DATE:
4/12/79
BY:
M.L.S.

DISPLACEMENT: 903 in³ (14.8 litre) ASPIRATION: TURBOCHARGED & AFTERCOOLED RATING:
BORE: 5.5 in (140 mm) STROKE: 4.75 in (121 mm) NO. OF CYLINDERS: 8 HP (kW) @ RPM
EMISSION CONTROL: AFC FUEL SYSTEM: PT 50 (373) @ 2600



Curves shown above represent engine performance capabilities at SAE standard J816b conditions of 500 ft. (150m) altitude (29.92" Hg (736mm Hg) dry barometer), 85°F (29°C) air intake temperature, and 0.34" Hg (5.6mm Hg) water vapor pressure with No. 2 diesel fuel.

STANDARDS DEPT.

CERTIFIED WITHIN 5%:

S. L. Gaal

CHIEF ENGINEER

Figure A-2. VTA-903T Engine Performance

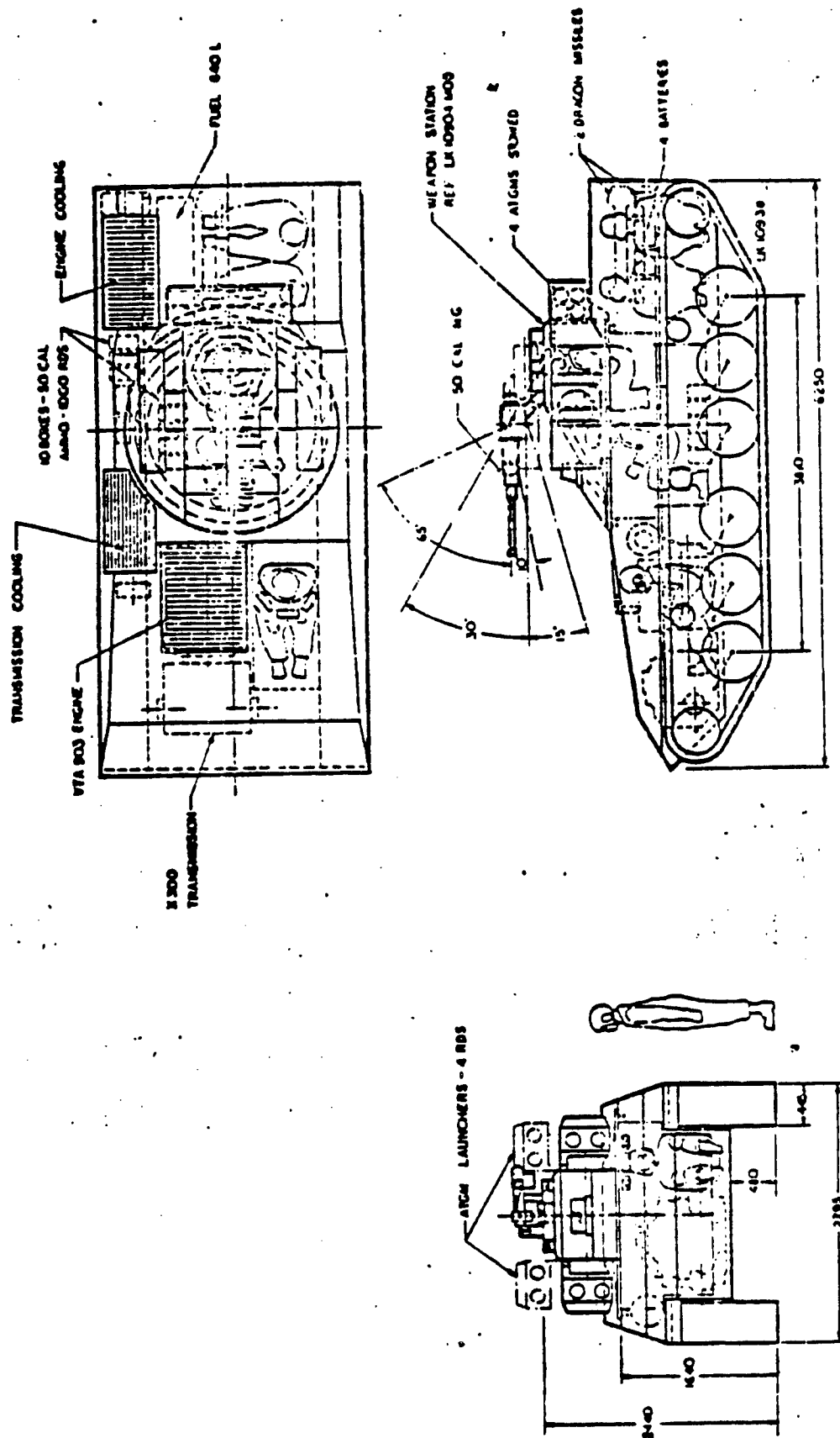


FIGURE A-3 19.5 Ton Baseline Drawing

40 Ton Vehicle Specification

1. General Vehicle Specifications:

Frontal Area	6.34 sq m (68.25 ft ²)
Gross Vehicle Weight	36.3 ton (<u>40 ton</u>)
Vehicle Top Speed (Governed)	73 Km/hr (45 mph)
Track Length (forward to aft roadwheel centerline)	4650 mm (183.07 in)
Distance between track (longitudinal centerline)	2790 mm (109.84 in)
Track Width	580 mm (22.83 in)

2. Propulsion System Specifications:

a. Transmission: (Electric Drive System)

The drive system shall provide automatic speed ratio control and inhibitors to prevent engine overspeed. Maximum output torque required shall be sufficient to generate a tractive effort of 427,000 Newtons, Reverse - 427,000 Newtons. There shall be tactile feedback to the driver when the transmission is in forward or reverse operational mode. The power train shall provide for safe, predictable performance for extended periods at speeds below 5 Km/hr.

b. Steer System:

A regenerative speed control system is required. Differential torque between sides shall be equal to maximum steer torque. Pivot steer capability on hard surface shall be 7 revolutions/min. The steering controls shall remain operative in the event of engine failure or vehicle towing. The steer system shall be capable of accepting full engine power.

c. Cooling Capability:

Capable of continuous tractive effort operation of at least 250,000 N.

d. Braking:

The vehicle shall be capable of a deceleration rate from maximum speed on level hard surface road at least 7 m/sec^2 (peak and 5 m/sec^2 (avg)). The vehicle shall be capable of an included hold with engine off on at least a 60% slope. The vehicle shall be capable of at least 25 stops from 60 Km/hr @ 5 m/sec^2 @ 3 minute intervals. The braking functions shall be accomplished by two separate mechanisms to allow redundancy for emergency purposes.

e. Electric/Hydraulic Power Capability:

Continuous operation of all vehicle and electrical and hydraulic systems shall be at least 7 Kw, to include silent watch - the silent watch is non-mobile, with noise, light, and smoke discipline. The above power requirement covers turret hydraulic, radio and other electrical needs, compartment ventilation and NBC countermeasure equipment. Electrical and hydraulic power sources must be capable of operating independently or in parallel of a stable self regulating manner. Average auxiliary power usage is 3.5 Kw.

f. Speed on Grade:

The propulsion on system shall be capable of sustaining forward vehicle speeds on hard surface roads and grades as defined in figure A-3.

g. Acceleration:

The vehicle shall be capable of acceleration on dry level surface from idle, from application of the throttle, in the forward direction from zero to 32.2 Km/hr (20 mph) in seven seconds; and in reverse direction from zero to 16 Km/hr (10 mph), in five seconds. Assume no "throttle" linkage delay.

h. Engine: See figures A-4 and A-5.

i. Shock:

The electric drive system must be able to withstand a 15 g shock load in any direction.

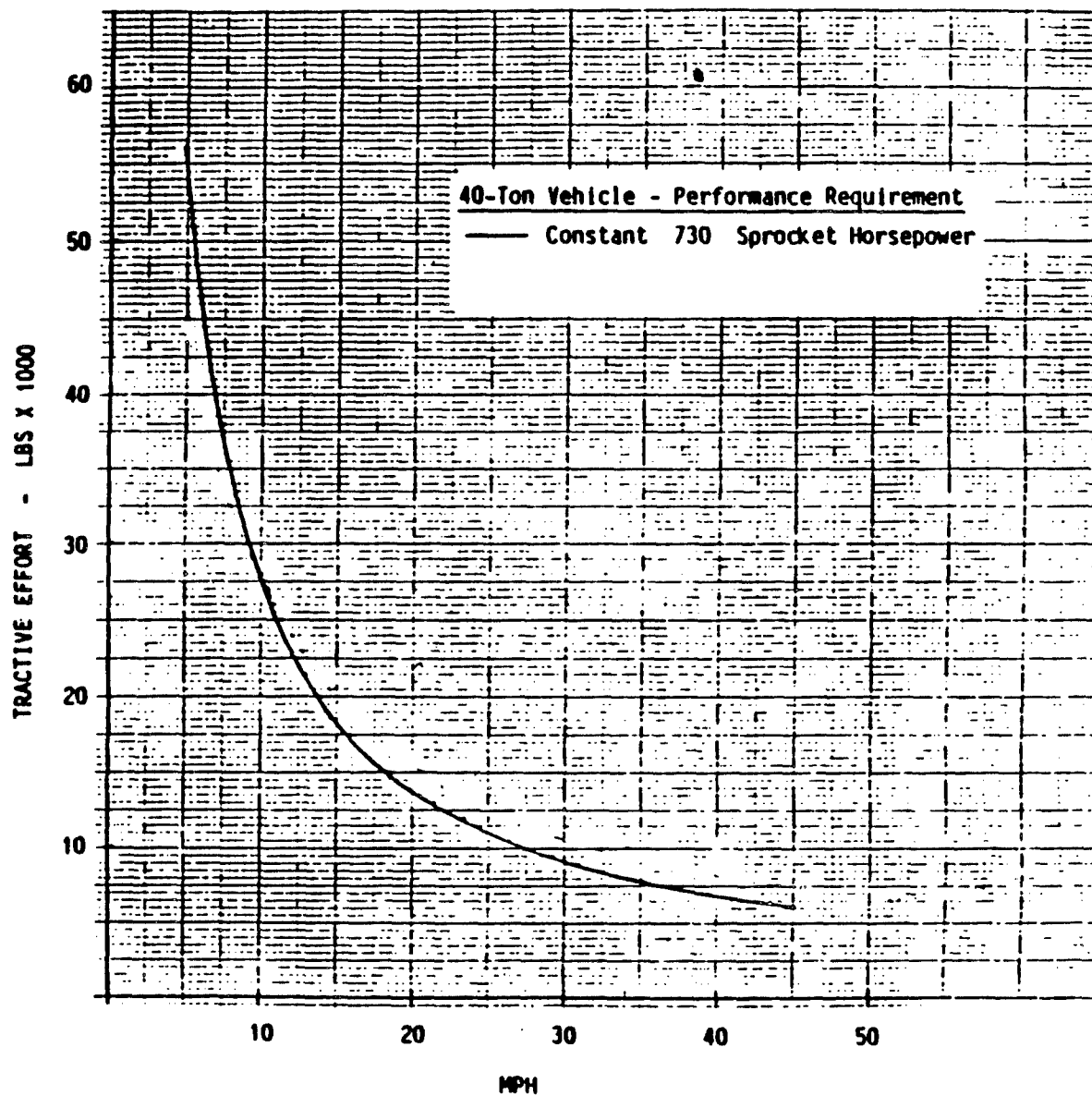


Figure A-4. Tractive Effort Versus Vehicle Speed

AD 1000

PROJECTION

ASSUMPTIONS:

• FAN HP = 12% GROSS HP

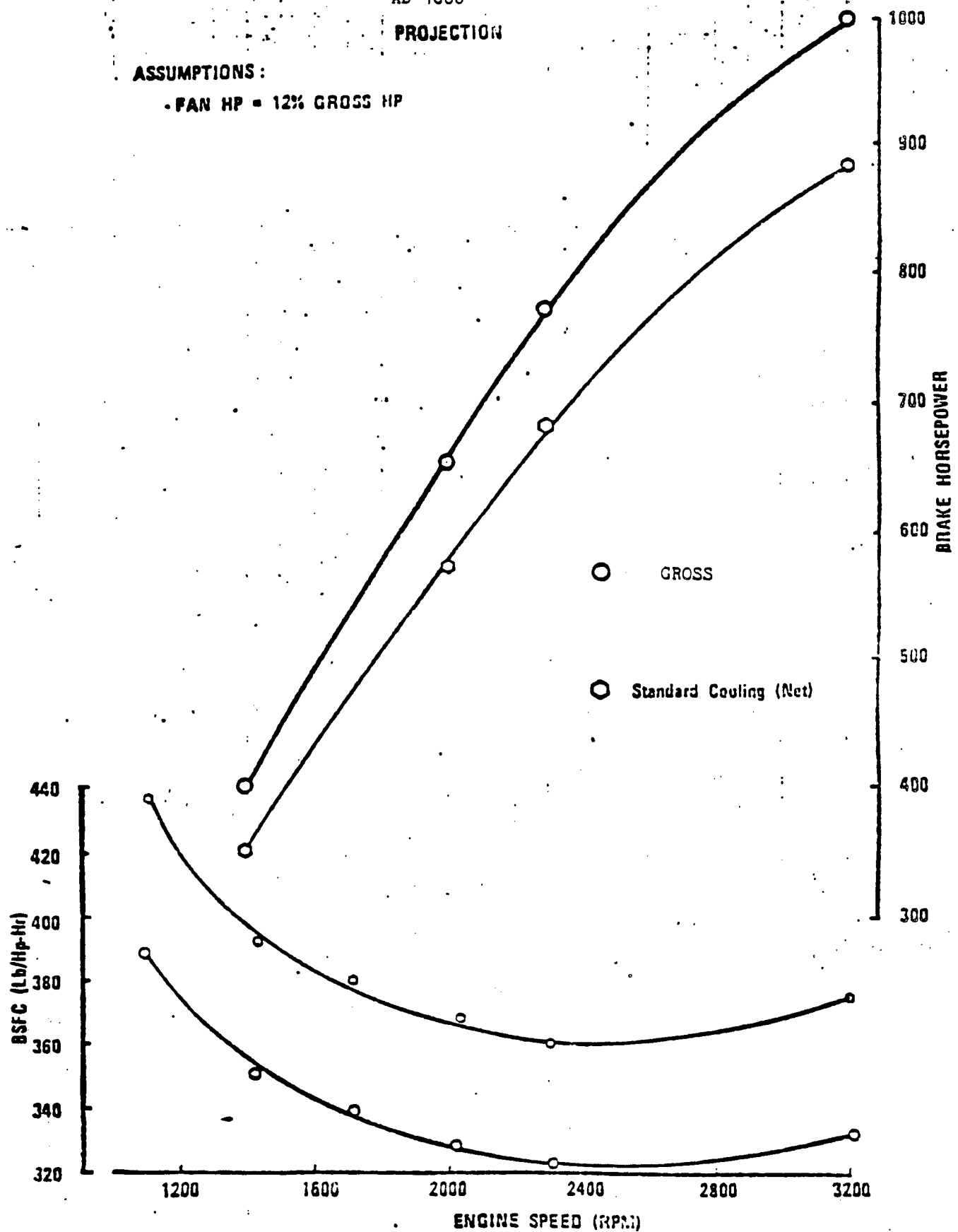


Figure A-5. AD1000 Engine Performance

APPENDIX B
ELECTRIC DRIVE CONCEPT CHARACTERISTICS AND DRAWINGS

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. I

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.5		.60	125	125	470	93.5	18000 rpm
2	PCU	19 x 17 x 14.5	2.70	5.40	256	512	218	96-93	
2	Traction Motor	13.5 dia x 12.4	1.02	2.04	330	660	192	93-90	4600-18000 rpm
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 6		.53		125		98	6.9:1 Ratio
2	2 Speed Gearbox	14 dia x 13.5	1.20	2.40	55	110		98-96	16.4:1 Lo 5.5:1 Hi
1	Oil Cooling System			3.00		360			Max Heat Rejection 4700 BTU/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cable			-		20			
				<u>15.20</u>		<u>2062</u>		76 avg. (73-78)	

GARRETT
PM GENERATOR AND MOTORS

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. 1

CONCEPT 2

Units Req'd	Unit	Size (In)	Unit		System		Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
			Volume Ft ³	Volume Ft ³	Volume Ft ³	Volume Ft ³					
1	Generator	13.3 dia x 10.6		.86			124		474	92	15000 rpm
2	PCU	14 x 14 x 14	1.57	3.14			94	188	213	96-90	
2	Traction Motor	4 Motor Cluster 11.4 dia x 9.5/ Motor	2.24	4.48			348	696	192	93-90	8000-24000 rpm
1	ECU	5 x 5 x 15		.22				12			
1	Transfer Case	14 dia x 6		.53				125		98	5.7:1 Ratio
2	2 Speed Gearbox	25 dia x 16 (Includes motors, brakes, gearbox)	3.0	6.00			111	222		98-96	24:1 Lo 8:1 Hi
1	Oil Cooling System			3.30				400			Max Heat Rejection 5430 BTU/Min
2	Brakes		.20	.40			55	110			
	Connector & Cable			-				40			
			<u>18.93</u>					<u>1917</u>		<u>74 avg.</u>	<u>(69-77)</u>

WESTINGHOUSE
CLUSTERED INDUCTION MOTORS AND
WOUND ROTOR BRUSHLESS GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TONCONF. ICONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	13.3 dia x 10.6		.60		125	477	92	15000 rpm
2	PCU	15.2 x 15.2 x 15.2	2.02	4.04	122	244	215	96-90	
2	Traction Motor	4 Motor Cluster 7.75 dia x 13.9/ Motor	1.52	3.04	180	360	192	91-89	8000-24000 rpm
1	ECU	7.5 x 5 x 15		.33		16			
1	Transfer Case	14 dia x 6		.53		125		98	5.7:1 Ratio
2	2 Speed Gearbox	25 dia x 16 (Includes motors, brakes, gearbox)	3.00	6.00	111	222		98-96	24:1 Lo 8:1 Hi
1	Oil Cooling System			3.30		400			Max Heat Rejection 5430 BTU/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cable					40			
			<u>18.24</u>			<u>1642</u>		<u>73 avg.</u> (69-74)	

WESTINGHOUSE
CLUSTERED PM MOTORS AND
WOUND ROTOR GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. I

CONCEPT 4

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	34.6 dia x 21.8		11.90		1191	417	92	2600 rpm Air Cooled
2	DC Traction Motor	16.9 dia x 18.1	2.35	4.70	700	1400	192	95-92	1880-5660 rpm
1	ECU	8 x 8 x 8		.30		20			Includes Motor Excitation System
2	2 Speed Gearbox	14 dia x 8	.75	1.50	40	80		98-96	6.6:1 Lo 2.2:1 Hi
1	Air Cooling System			3.00		75			Centrifugal Filter & Ducting
2	Brakes		.20	.40	55	110			Max Heat Rejection 3400 BTU/Min
	Connectors & Cable		-			15			
			<u>21.8</u>			<u>2891</u>		83 avg. (81-85)	

ACEC DC MOTORS
AND RECTIFIED AC GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. 1

CONCEPT 5

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 9.3		.53	110	110	417	93.5	18000 rpm
2	DC Traction Motor	16.9 dia x 18.1	2.35	4.70	700	1400	192	95-92	1880-5660 rpm
1	Rectifier	12 x 12 x 12		1.00	100	100		98	
1	ECU	8 x 8 x 8		.30		20			Includes Motor Excitation System
2	2 Speed Gearbox	14 dia x 8	.75	1.50	40	80		98-96	6.7:1 Lo 2.2:1 Hi
1	Transfer Case	14 dia x 6		.53		125		98	6.9:1 Ratio
1	Cooling System Air & Oil			2.00		200			Max Heat Rejection 3440 BTU/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cables					15			
			<u>11.93</u>			<u>2160</u>		81 avg. (80-84)	

ACEC DC MOTORS
AND GARRETT PM GENERATOR
RECTIFIED TO DC

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. 1CONCEPT 6

Units Req'd	Unit	Size (In)	Unit		System		Rating HP	Efficiency %	Remarks
			Volume Ft ³	Weight (Lbs)	Volume Ft ³	Weight (Lbs)			
1	Generator	11.2 dia x 10.5			.60	125	444	93.5	18000 rpm
6	CC	11.6 x 11.6 x 11.6	1.90	90	5.40	540	218	96	
4	Traction Motor	13.5 dia x 9.05	.75	246	3.00	984	173	93-90	4600-18000 rpm
1	ECU	12 x 10 x 12			.83	40			
1	Transfer Case	14 dia x 6			.53	125		98	6.9:1 Ratio
2	Combining Gearbox	14 dia x 8	.75	80	1.50	160		98-96	16.4:1 5.5:1
1	Oil Cooling System				2.80	360			Max Heat Rejection 4000 BTU/Min
2	Brakes		.20	55	.40	110			
	Connectors and Cables					20			
			<u>15.06</u>			<u>2464</u>		78 avg. (76-80)	

GARRETT PM MOTOR COMBINATION
(2 MOTORS/SPROCKET) AND PM
GENERATOR WITH CONTROLLER

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. I

CONCEPT 7

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	DC Homopolar Generator	16 dia x 17.5		2.03		670	440	95	3000 amp/in ² 10400 rpm
2	DC Homopolar Traction Motor	16.5 dia x 19.0	2.35	4.70	800	1600	200	92	3000 amp/in ² 1040-10400 rpm
2	Single Speed Gearbox	14 dia x 8	.75	1.50	60	120		98	4:1 Ratio
1	ECU	7.5 x 5 x 5		.30		16			
1	Transfer Case	14 dia x 6		.53		125		98	4:1 Ratio
1	Oil Cooling System			2.6		330			Max Heat Rejection 3070 BTU/Min
2	Brakes		.20	.40	55	110			
	Buss	2 x 3 x 64		.20		120			
	Excitation System			1.90		100			
	Contactors			.3		120			
				<u>14.46</u>		<u>3391</u>		83 avg.	

WESTINGHOUSE DC HOMOPOLAR
GENERATOR AND MOTORS

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. I

CONCEPT 8

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
2	AC Homopolar Generator	14 dia x 11.2	1.00	2.00	330	660	250	93	12000 rpm
2	Traction Motor	4 Motor Cluster 11.4 dia x 9.5/ Motor	2.24	4.48	348	696	192	93-90	8000-24000 rpm
2	2 Speed Gearbox	25 dia x 16 (Includes motors, brakes, gearbox)	3.00	6.00	111	222		98-96	24:1 Lo 8:1 Hi
1	Transfer Case	14 dia x 6		.53		125		98	4.6:1
1	Oil Cooling			2.90		360			Max Heat Rejection 4160 BTU/Min
2	Brakes		.20	.40	55	110			
1	Excitation System			1.90		100			
	Cables & Connectors					40			
			<u>18.2</u>			<u>2313</u>		80 avg. (77-83)	

U OF M AC HOMOPOLAR GENERATOR AND
WESTINGHOUSE INDUCTION MOTOR CLUSTER

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. I

CONCEPT 9

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 9.8		.56		103	416	93.5	18000 rpm
1	Rectifier	12 x 12 x 12		1.00		100	408	98	Oil Cooled
2	Motor Controller	12.8 x 12.8 x 12.8	1.20	2.40	75	150	400	98	Oil Cooled
2	Traction Motor	13 dia x 6.5	.50	1.00	110	220	250	96	Elect. Shift Air Cooled
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 6		.53		125		98	6.9:1 Ratio
2	Single Speed Gearbox	14 dia x 8	.75	1.50	60	120		98	4:1 Ratio
1	Air & Oil Cooling System			3.00		200			Max Heat Rejection 3260 BTU/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cables		-			20			
			<u>11.22</u>			<u>1188</u>		82 avg.	

UNIQUE MOBILITY SELF-SYNC MOTORS
AND GARRETT PM GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. I

CONCEPT 10

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.5		.60		125	444	93.5	18000 rpm
3	PCU	12 x 10 x 12	.83	2.50	83	250	218	96	
2	Traction Motor	13.5 dia x 12.4	1.02	2.04	330	660	192	93-90	4600-18000 rpm
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 6		.53		125		98	6.9:1 Ratio
2	2 Speed Gearbox	14 dia x 13.5	1.25	2.50	55	110		98-96	16.4:1 Lo 5.5:1 Hi
1	Oil Cooling System			2.80		360			Max Heat Rejection 4000 BTU/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cables		-			20			
			<u>12.20</u>			<u>1800</u>		78 avg. (76-80)	

GARRETT PM MOTORS AND
GENERATOR WITH MODIFIED PCU'S

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. IA

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.5		.60	125	125	470	93.5	Oil Cooled 18000 rpm
4	PCU	16 x 16 x 13	1.95	7.80	170	680	110	96-93	Oil Cooled
4	Traction Motor	13.5 dia x 8.5	.75	3.00	210	840	96	93-90	Oil Cooled 4600-18500 rpm
4	2 Speed Gearbox	12 dia x 12	.80	3.20	75	300		98-96	Includes Brakes 16.4:1 Lo 5.5:1 Hi
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 6		.53		125		98	6.9:1 Ratio
1	Oil Cooling System			3.0		370			Max Heat Rejection 4700 BTU/Min
	Cables & Connectors					60			
				<u>18.96</u> (12.76 in Hull)		<u>2590</u> 2540		76 avg. (73-78)	

GARRETT PM GENERATOR AND MOTORS
(MOTOR AND GEAR BOX MOUNTED INSIDE SPROCKET -
FOUR DRIVE SPROCKETS)

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. 1A

CONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.5		.60	110	110	420	93.5	18000 rpm Oil Cooled
4	PCU	12 x 12 x 12	1.0	4.0	60	240		90-92	Oil Cooled
4	VR Traction Motor	23 dia x 31	7.4	29.2	870	3480	93		70 rpm - 630 rpm Air Cooled
1	ECU	8 x 8 x 8		.3		40			
1	Transfer Case	14 dia x 6		.5		125		98	6.9:1 Ratio
4	Brakes			.8	40	160			
1	Cooling System (Air & Oil)			3.0		200			Max Heat Rejection 3260 BTU/Min
	Connectors & Cable				20				
				<u>38.4</u>		<u>4375</u>		83 avg. (82-84)	

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. IA

CONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.5		.60		110	420	93.5	18000 rpm Max
4	PCU	12 x 9 x 12	.75	3.0	44	176		90-92	
4	VR Traction Motor	14.9 dia x 8.89	.90	3.60	176	704	93		240 rpm - 2160 rpm
1	ECU	8 x 8 x 8		.3		40			
1	Transfer Case	14 dia x 6		.5		125		98	
4	Single Speed G.B. (Final Drive)	12 dia x 8	.5	2.00	50	200		98	2.5:1 Ratio
4	Brakes		.2	.8	40	160			
1	Cooling System			3.0		200			Max Heat Rejection 3620 BTU/Min
	Connectors & Cable			-		20			
			<u>13.8</u>			<u>1735</u>		81 avg. (80-82)	

JARRET VR MOTOR AND
GARRET PM GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. II

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 12.1		.62	125	125	484	93.5	18000 rpm
1	PCU	18 x 18 x 18		3.42	330	330	450	96-93	
1	Traction Motor	13.5 dia x 20.0		1.04	340	340	401	94-89	46000-18500 rpm
1	ECU	12 x 10 x 12		.83	40	40			
1	Transfer Case	14 dia x 6		.53	125	125		98	6.9:1 Ratio
1	Steer Motor	12 dia x 10		.65	80	80			
1	Steer Gearbox (Single Speed)			1.20	110	110			
1	Steer PCU	20 x 14 x 5.6		.90	95	95			
1	2 Speed Gearbox	14 dia x 13.5		1.20	80	80		98-96	16:1 Lo 4:1 Hi
2	Brakes		.20	.40	55	110			
2	Prop Shafts			.80	85	85			
	Connectors & Cable			-	20	20			
1	Oil Cooling System			3.00	360	360			Max Heat Rejection 4185 BTU/Min
				<u>14.59</u>		<u>1900</u>		76 avg. (73-78)	

GARRETT
PM MOTOR AND GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. II

CONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	13.3 dia x 10.3		.85	125	125	468	92	15000 rpm
1	PCU	18.2 x 18.2 x 18.2		3.50	210	210	422	96-90	
1	Traction Motor	4 Motor Cluster 7.75 dia. x 17.5		1.92	340	340	384	93-91	8000-24000 rpm
1	ECU	7.5 x 5 x 15		.33	16	16			
1	Transfer Case	14 dia x 6		.53	125	125		98	5.7:1
1	2 Speed Gearbox	27 dia x 20 (Includes motors, brakes, gearbox)		3.0	156	156		98-96	24:1 Lo 8:1 Hi
1	Oil Cooling System			3.3	400	400			Max Heat Rejection 5430 BTU/Min
2	Shafts			.8	85	85			
1	Steer Motor	12 dia x 10		.65	80	80			
1	Single Speed Gearbox			1.20	110	110			
1	Steer PCU	20 x 14 x 5.6		.9	95	95			
	Cable & Connectors				20	20			
2	Brakes		.2	.4	55	110			
			<u>17.38</u>		<u>1872</u>			73 avg.	

WESTINGHOUSE GENERATOR, PM CLUSTER MOTOR AND PM STEER MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5

CONF. II

CONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 12		.59	110		436	93.5	Oil Cooled 18000 rpm
1	DC Traction Motor	22 dia x 17.3		3.81	1046		401	95-92	Air Cooled
1	Rectifier	12 x 12 x 12		1.00	100			98	
1	ECU	8 x 8 x 8		.30	20				
1	Transfer Case	14 dia x 6		.53	125			98	6.9:1 Ratio
1	Steer Motor	12 dia x 10		.65	80				
1	Steer Gearbox (Single Speed)			1.20	110				
1	Steer PCU	20 x 14 x 5.6		.90	95				
1	2 Speed Gearbox	14 dia x 8		.75	60			98-96	
2	Brakes		.20	.40	55	110			
2	Prop Shaft			.80	85				
	Connectors & Cable								Max Heat Rejection 3968 BTU/Min
1	Cooling System Oil & Air			3.00	200				

81 avg. (80-84)

2151

GARRETT
PM GENERATOR AND ACEC DC MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TONCONF. IICONCEPT 4

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	DC Homopolar Generator	16 dia x 17.5		2.03		670	440	95	3000 amp/in ² 10400 rpm
1	DC Homopolar Motor	17 dia x 25		3.28		1250	400	95	3000 amp/in ² 1040-10400 rpm
1	Transfer Case	14 dia x 6		.53		125		98	4:1 Ratio
1	Single Speed Gearbox	14 dia x 8		.75		80		98	4:1 Ratio
1	Steer Motor	12 dia x 10		.65		80			
1	Steer PCU	20 x 14 x 5.6		.90		95			
1	Single Speed Steer Gearbox			1.20		110			
1	Oil Cooling System			2.50		320			Max Heat Rejection 2730 BTU/Min
1	ECU	8 x 8 x 8		.30		16			
2	Brakes		.2	.40	55	110			
	Buss			.20		120			
	Excitation System (Steer Power Gen)			1.9		100			
	Shafts			.8		85			
				<u>15.44</u>		<u>3161</u>		85 avg.	

WESTINGHOUSE
DC HOMOPOLAR GENERATOR AND MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. II

CONCEPT 5

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	AC Homopolar Generator	10 dia x 21		1.4		467	500	934	12000 rpm
1	Traction Motor	4 Motor Cluster 10.4 dia x 13.7/ Motor		2.7		540	384	93-91	8000-24000 rpm
1	ECU			.2		12			
1	Transfer Case	14 dia x 6		.5		125		98	4.6:1
1	2 Speed Gearbox	27 dia x 20 (Includes motors, brakes, gearbox)		3.0		156		98-96	24:1 Los 8:1 Hi
2	Shafts			.8		85			
1	Single Speed Gearbox			1.20		110			
1	Oil Cooling System			2.9		360			Max Heat Rejection 4160 BTU/Min
2	Brakes		.20	.4	55	110			
1	Steer Motor	12 dia x 10		.6		80			
1	Steer PCU	20 x 14 x 5.6		.9		95			
	Cables & Connectors					20			
				16.5		2260		80 avg. (77-83)	

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AC HOMOPOLAR GENERATOR AND WESTINGHOUSE INDUCTION MOTOR CLUSTER

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5

CONF. II
CONCEPT 6

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.2		.58	105	105	416	93.5	18,000 RPM
1	Rectifier	12 x 12 x 12		1.00	100	100	408	98	Oil Cooled
1	Motor Controller	12.8 x 12.8 x 12.8		2.40	150	150	400	98	Oil Cooled
1	Traction Motor	16.5 dia x 8		.99	210	210	384	96	Elec. Shift Air Cooled
1	ECU	8 x 8 x 8		.3	20	20			
1	Transfer Case	14 dia x 6		.53	125	125		98	6.9:1 Ratio
1	Traction Single Speed GB	14 dia x 8		.75	80	80		98	
1	Steer Motor	12 dia x 10		.60	80	80			
1	Steer Motor Controller	20 x 14 x 5.6		.90	95	95			
1	Steer Single Speed GB			1.20	110	110			
2	Brakes			.4	110	110			
2	Prop Shafts			.8	85	85			
1	Cooling System			3.0	200	200			Max Heat Rejection 3260 BTU/Min
	Cables & Connectors				20	20			
				<u>13.45</u>		<u>1490</u>		82 avg.	

GARRETT GENERATOR W/UNIQUE MOBILITY SELF-SYNC MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. III

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 10.5		.60		125	470	93.5	18000 rpm
2	PCU	20 x 14 x 16	2.40	4.80	220	440	218	96-63	
2	Traction Motor	13.5 dia x 9	.66	1.32	230	460	192	93-88	4600-18500 rpm
1	Steer Motor	8 dia x 14		.40		45	360		25000 rpm
1	Steer PCU	20 x 14 x 5.6		.90		95			
1	Steer Gearbox	20 x 14 x 5.6		1.20		110			
1	Transfer Case	14 dia x 6		.53		125		98	6.9:1
1	ECU	12 x 10 x 12		.80		40			
2	2 Speed Gearbox	14 dia x 13.5	1.20	2.40	55	110		98-96	16:1 Lo 4:1 Hi
1	Oil Cooling System			3.00		360			Max Heat Rejection 4185 BTU/Min
2	Brakes		.2	.40		110			
1	Steer Shaft			.40		40			
	Cables & Connectors					20			
			<u>16.75</u>			<u>2080</u>		76 (73-78) avg.	

GARRETT
PM GENERATOR, PROPULSION MOTORS AND STEER MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TONCONF. IIICONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 9.3		.53	110		417	93.5	18000 rpm
2	DC Traction Motor	16.9 dia x 11.7	1.52	3.04	488	976	192	95-92	1880-5660 rpm
1	Rectifier	12 x 12 x 12		1.00		100		98	
1	Steer Motor	8 dia x 14		.40		45	360		25000 rpm
1	Steer PCU	20 x 14 x 5.6		.90		95			
1	Steer Gearbox			1.20		110			
1	Transfer Case	14 dia x 6		.53		125		98	6.9:1 Ratio
1	ECU	8 x 8 x 8		.30		20			
2	2 Speed Gearbox	14 dia x 8	.75	1.50	40	80		98-96	6.6:1 Lo 2.2:1 Hi
1	Air & Oil Cooling System			3.00		200			Max Heat Rejection 3440 BTU/Min
2	Brakes		.20	.40	55	110			
1	Steer Shaft			.40		40			
	Cables & Connectors					20			
			<u>13.20</u>			<u>2031</u>		81 avg. (80-84)	

ACEC DC MOTORS

GARRETT PM GENERATOR RECTIFIED TO DC

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. III

CONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 9.8		.56		103	400	93.5	18000 rpm
1	Rectifier	12 x 12 x 12		1.00		100	400	98	Oil Cooled
2	Motor Controller	12.8 x 12.8 x 12.8	1.20	2.40	75	150	210	98	Oil Cooled
2	Traction Motor	13 dia x 6.5	.50	1.00	110	220	250	96	Electric Shift Air Cooled
1	Steer Motor	8 dia x 14		.40		45	360		
1	Steer PCU	20 x 14 x 5.6		.90		95			
1	Steer Gearbox		1.20			110			
1	Transfer Case	14 dia x 6		.53		125			6.9:1 Ratio
1	ECU	12 x 10 x 12		.83		40			
2	Single Speed Gearbox	14 dia x 8	.75	1.50	60	120			4:1 Ratio
1	Air & Oil Cooling System			3.00		200			
2	Brakes		.20	.40	55	110			
1	Steershaft			.40		40			
	Cables & Connectors					20			
			<u>14.12</u>			<u>1478</u>		82 avg.	

UNIQUE MOBILITY SELF-SYNC MOTORS AND
GARRETT PM GEN AND STEER MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. IV

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	PM Generator	11.2 dia x 10.5	.60		125		470	93.5	18000 rpm Oil cooled
2	PCU	16 x 16 x 16	2.40	4.80	220	440	218	96-93	
2	PM Traction Motor	13.5 dia x 9	.68	1.36	225	450	192	93-88	4600-18000 rpm 2.0 pw
1	ECU	12 x 10 x 12	.80			40			
1	Transfer Case w/Clutch & Brake	14 dia x 9	.80			150		98	6.9:1 Ratio
2	2 Speed GB	14 dia x 13.5	1.20	2.40	55	110		96-98	16:1 Lo 10:1 Hi
2	Combining Gearbox	14 dia x 8	.75	1.50	80	160		98	
1	Right Angle Gearbox	12 x 12 x 12		1.00		120		96	
1	Oil Cooling System			3.00		360			Max Heat Rejection 4890 BTU/Min
2	Brake Connectors & Cable			.40		110			
3	Shafts			.40		50			
			<u>17.06</u>			<u>2145</u>		<u>80 avg. (73-88)</u>	

DUAL PATH CONCEPT W/GARRETT
PM GENERATOR AND PM TRACTION MOTORS

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 19.5 TON

CONF. IV

CONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 12		.56		103	417	93.5	18000 rpm
1	Rectifier	12 x 12 x 12		1.00		100	400	98	
2	Traction Motors	13 dia x 6.5	.50	1.00	110	220	192	96	10000 rpm, Electric Shift, Air Cooled
2	Motor Controllers	12.8 x 12.8 x 12.8	1.20	2.40	75	150	210	98	
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case w/clutch and brake	10 x 10 x 12		.69		125		98	6.9:1 Ratio
2	Single Speed Combining Gearbox	14 dia x 8	.75	1.50	.80	160		98	Variable Ratio
2	Brakes			.40		110			
1	Air & Oil Cooling System			3.00		200			Max Heat Rejection 3260 BTU/Min
1	Cross Drive Gearbox	12 x 12 x 12		1.00		120		98	
3	Shafts			.30		80			
	Connectors & Cables					30			
				<u>13.69</u>		<u>1558</u>			(82-91) 86 avg.

UNIQUE MOBILITY PM MOTOR
GARRETT PM GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS
VEHICLE GVW 19.5 TON
CONF. IV
CONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 9.3		.53		110	417	93.5	18000 RPM
2	DC Traction Motor	16.9 dia x 12.1	1.57	3.14	477	954	192	95-92	1800-5660 RPM
1	Rectifier	12 x 12 x 12		1.00		100		98	
1	ECU	8 x 8 x 8		.30		20			Includes Motor Excitation System
1	Transfer Case w/Clutch & Brake	14 dia x 9		.80		150		98	6.9:1 Ratio
2	2 Speed Gearbox	14 dia x 8	.75	1.50	40	80		98-96	6.6:1 Lo 2.2:1 Hi
2	Combining Gearbox	14 dia x 8	.75	1.50	80	160		98	
1	Right Angle Gearbox	12 x 12 x 12		1.00		120			
1	Air & Oil Cooling System			3.00		200			Max Heat Rejection 3449 BTU/Min
2	Brakes		.20	.40	55	110			
	Connectors & Cables					30			
3	Shafts		.40			50			
			<u>13.57</u>			<u>2084</u>		84 avg. (80-90)	

ACEC DC MOTORS
GARRETT PM GENERATOR RECTIFIED TO DC

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. 1

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 16.3		.93		244	941	94.5	18000 rpm
2	PCU	20 x 24.4 x 14	3.95	7.90	480	960	438	96-93	
2	Traction Motor	13.5 dia x 20	1.66	3.32	530	1060	385	94-88	4600-18000 rpm
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 7.3		.65		150		98	5.6:1 Ratio
2	2 Speed Gearbox	14 dia x 13.5	1.20	2.40	80	160		98-96	16:1 Lo 4:1 Hi
1	Oil Cooling System			4.40		510			Max Heat Rejection 9420 BTU/Min
2	Brakes		.4	.8	110	220			
	Connectors & Cables					30			
			<u>21.23</u>			<u>3374</u>		<u>77 avg. (74-80)</u>	

GARRETT CONCEPT W/PM GENERATOR AND MOTORS

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. 1

CONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 15.1		.86		217	837	94.5	18000 rpm
2	DC Traction Motors	22 dia x 24.8	5.45	10.90	1450	2900	385	95-92	1150-3460 rpm
1	Rectifier	14.5 x 14.5 x 14.5		1.75		180		98	
1	ECU	10 x 10 x 10		.60		33			Includes Excitation System
2	2 Speed Gearbox	14 dia x 9	.80	1.60	60	120		98-96	6.6:1 Lo 2.2:1 Hi
1	Transfer Case	14 dia x 7.3		.65		150		98	5.6:1 RATIO
1	Cooling System (Oil & Air)			4.00		250			Max Heat Rejection 7250 BTU/Min
2	Brakes		.40	.80	110	220			
	Connectors & Cables					20			
				<u>21.16</u>		<u>4090</u>		<u>83</u>	(80-85) avg.

ACEC DC MOTORS AND
GARRETT PM GENERATOR RECTIFIED TO DC

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. 1

CONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 15.8		.90	230	230	890	94.5	18000 RPM
3	PCU	13.2 x 13.2 x 13.2		4.00	400	400	426	96	
2	Traction Motor	13.5 dia x 20	1.66	3.32	525	1050	388	94-88	4600-18500 rpm
1	ECU	12 x 10 x 12		.83	40	40			
1	Transfer Case	14 dia x 7.3		.65	158	158		98	5.6:1 Ratio
2	2 Speed Gearbox	14 dia x 13.5	1.20	2.40	80	160		98-96	
1	Oil Cooling System			4.20	480	480			Max Heat Rejection 8330 BTU/Min
2	Brakes		.2	.40	110	220			
	Connectors & Cables				50	50			
			<u>16.7</u>			<u>2780</u>		79 avg. (77-81)	

GARRETT PM GENERATOR AND MOTORS, W/ MODIFIED PCU'S

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. 1

CONCEPT 4

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	DC Homopolar Generator	16.5 dia x 22		2.72		960	880	95	3000 amp/in ² 10400 rpm
2	DC Homopolar Traction Motor	17 dia x 25	3.28	6.56	1250	2500	400	95	3000 amp/in ² 1040-10400 rpm
2	Single Speed Gearbox	14 dia x 9	.80	1.60	80	160		98	4:1 Ratio
1	ECU	7.5 x 5 x 15		.30		16			
1	Transfer Case	14 dia x 7.3		.65		150		98	3.1:1 Ratio
1	Oil Cooling System			3.30		400			Max Heat Rejection 5440 BTU/Min
2	Brakes		.40	.80	110	220			
	Buss	4 x 3 x 64		.40		240			
	Excitation System			2.90		150			
	Contactors			.3		120			
				<u>19.53</u>		<u>4916</u>		85 avg.	

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. 1

CONCEPT 5

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
2	AC Homopolar Generator	14 dia x 15.7	1.4	2.8	467	934	500	93.4	12000 rpm
2	Traction Motor	10.4 dia x 13.8/ Motor (4 motor cluster)	2.72	5.44	532	1064	385	93-90	8000-24000 rpm
2	2 Speed Gearbox	27 dia x 20 (Includes motors, brakes and gearbox)	3.0	6.0	156	312		98-96	24:1 Lo 8:1 Hi
1	Transfer Case	14 dia x 7.3		.65		150		98	3.75:1
1	Oil Cooling System			4.20		480			Max Heat Rejection 8330 BTU/Min
2	Brakes		.40	.80	110	220			
	Cables & Connectors					60			
			<u>22.79</u>			<u>3370</u>		82 avg. (77-85)	

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U OF M HOMOPOLAR GENERATOR AND WESTINGHOUSE INDUCTION MOTOR CLUSTER

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. I

CONCEPT 6

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 15.1		.86		217	837	94.5	18000 rpm
1	Rectifier	14.5 x 14.5 x 14.5		1.75		180		98	Oil Cooled
2	Motor Controller	15.9 x 15.9 x 15.	2.33	4.66	140	280	420	98	Oil Cooled
2	Traction Motor	16.50 dia x 8	.99	1.98	210	420	400	96	Air Cooled
2	Single Speed Gearbox	14 dia x 8	.75	1.50	80	160		98	
1	ECU	12 x 10 x 12		.83		40			
1	Transfer Case	14 dia x 7.3		.65		150		98	5.6:1 Ratio
1	Cooling System (Air & Oil)			4.00		250			
2	Brakes		.40	.80	110	220			
	Cables & Connectors					20			
			<u>17.03</u>			<u>1937</u>		83 avg.	

UNIQUE MOBILITY SELF-SYNC MOTORS/GARRETT PM GENERATOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TONCONF. IICONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	DC Homopolar Generator	16.5 dia x 22		2.72	960	960	880	95	3000 amp/in ² 10400 rpm
1	DC Homopolar Motor	17 dia x 35		4.60	1800	1800	800	95	3000 amp/in ² 1040-10400 rpm
1	Transfer Case	14 dia x 7.3		.65	150	150		98	3.1:1 Ratio
1	Single Speed Gearbox	14 dia x 11.2		1.00	110	110		98	4:1 Ratio
1	Steer Motor & Controls	12 dia x 12 12 x 12 x 12		1.75	200	200			
1	Single Speed Gearbox			1.20	130	130			
1	Oil Cooling System			3.30	400	400			Max Heat Rejection 5440 BTU/Min
1	ECU	7.5 x 5 x 15		.30	16	16			
2	Brakes	4 x 3 x 64	.40	.80	110	220			
	Buss			.4	240	240			
	Excitation System			2.90	150	150			
	Shafts			.8	100	100			
				<u>20.42</u>		<u>4466</u>		85 avg.	

WESTINGHOUSE DC HOMOPOLAR GENERATOR AND MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. II

CONCEPT 2

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	AC Homopolar Generator			2.1		700	1000	93.4	12000 rpm
1	Traction Motor	(6 Motor Cluster)	.78	4.68	165	990	770	94-91	8000-24000 rpm
1	ECU	7.5 x 5 x 15		.3		16			
1	Transfer Case	14 dia x 7.3		.65		150		98	3.75:1 Ratio
1	2 Speed Gearbox	27 dia x 20 (Includes motors, brakes and gearbox)		3.0		200		98-96	24:1 Lo 8:1 Hi
2	Shafts			.8		100			
1	Oil Cooling System			4.20		470			Max Heat Rejection 8330 BTU/Min
2	Brakes		.40	.80	110	220			
1	Steer Motor & PCU	12 dia x 12 12 x 12 x 12		1.75		200			
1	Single Speed Gearbox			1.20		130			
	Cables & Connectors					30			
				<u>22.38</u>		<u>3366</u>		82 avg. (77-85)	

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. II

CONCEPT 3

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	13.3 dia x 20.9		1.68		242	940	93	15000 rpm
1	PCU	23 x 23 x 23		7.0		405	846	96-90	
1	Traction Motor (6 Motor Cluster)	7.75 dia x 18.8	.54	3.24	114	680	770	93-91	8000-24000 rpm
1	ECU	7.5 x 5 x 15		.33		16			
1	Transfer Case	14 dia x 7.3		.65		150		98	4:7:1
1	2 Speed Gearbox	27 dia x 20 (Includes motors, brakes and gearbox)		3.0		200		98-96	24:1 Lo 8:1 Hi
1	Oil Cooling System			4.40		510			Max Heat Rejection 9420 BTU/Min
2	Shafts			.8		100			
1	Steer Motor & PCU	12 dia x 12 12 x 12 x 12		1.75		200			
1	Single Speed Gearbox			1.20		130			
	Cable & Connectors					30			
2	Brakes		.40	.80	110	220			
			<u>24.85</u>			<u>2883</u>		77 avg. (74-81)	

WESTINGHOUSE GENERATOR, PM CLUSTER MOTOR AND PM STEER MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. II

CONCEPT 4

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 15.1		.86	220	220	835	94.5	18000 RPM
1	Rectifier	14.5 x 14.5 x 14.5		1.75	180	180	818	98	Oil Cooled
1	PCU	19.5 x 19.5 x 19.5		4.30	270	270	802	98	Oil Cooled
1	Traction Motor 4 (Motor Cluster)	13 dia x 6.5/Motor		2.00	440	440	770	96	Elec. Shift Air Cooled
1	Transfer Case	14 dia x 7.3		.65	150	150		.98	5.6:1 RATIO
1	Single Speed Gearbox	14 dia x 11.2		1.00	120	120		.98	
1	ECU	8 x 8 x 8		.30	20	20			
1	Oil & Air Cooling System			4.00	250	250			Max Heat Rejection 6160 BTU/Min
2	Shafts			.80	100	100			
1	Steer Motor	12 dia x 12		.80	110	110			
1	Steer PCU	12 x 12 x 12		1.00	90	90			
1	Single Speed GB (Steer)			1.20	130	130			
2	Brakes			.80	220	220		83 avg.	
	Cables & Connectors				30	30			
				<u>19.46</u>		<u>2330</u>			

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. III

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 16.3		.93	242	242	940	94.5	18000 rpm
2	PCU	20 x 14 x 20.1	3.40	6.80	325	650	438	96-93	Oil Cooled
2	Traction Motor	13.5 dia x 12.3	1.02	2.04	335	670	385	94-88	4600-18500 rpm
1	Steer Motor	8 dia x 18		.50	72	72			
1	Steer PCU	20 x 14 x 8.5		1.40	140	140			
1	Transfer Case	14 dia x 7.3		.65	150	150		98	5.6:1 RATIO
1	ECU	12 x 10 x 12		.80	40	40			
2	2 Speed Gearbox	14 dia x 13.5	1.20	2.40	80	160		96-98	
1	Oil Cooling System			4.40		510			Max Heat Rejection 9420 BTU/Min
2	Brakes		.40	.80	110	220			
1	Gearbox			1.20		130			
1	Shaft			.40		50			
	Cables & Connectors					30			
			<u>22.30</u>			<u>3064</u>		77 avg. (74-80)	

GARRETT PM GENERATOR, PROPULSION MOTORS, AND STEER MOTOR

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

CONF. IV

CONCEPT 1

Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	PM Generator	11.2 dia x 16.3		.93		242	941	94.5	18000 rpm Oil Cooled
2	PCU	20 x 14 x 20.1	3.40	6.80	325	650	438	96-93	
2	PM Traction Motor	13.5 dia x 12.3	1.02	2.04	335	670	385	94-88	46000-18000 rpm 2.0 PU
1	ECU	12 x 10 x 12		.80		40			
1	Transfer Case w/Clutch & Brake	14 dia x 10.8		.96		180		98	5.6:1 Ratio
2	Variable Ratio Gearbox	14 dia x 8	.75	1.50	100	200		97	
1	Right Angle Gearbox	12 x 12 x 12		1.00		150		96	
1	Oil Cooling System			4.40		510			Max Heat Rejection 9420 BTU/Min
	Connectors & Cables					40			
3	Shafts			.40		60			
2	Brakes		.40	.80	110	220			
			<u>20.53</u>			<u>2962</u>		83 avg. (74-90)	

DUAL PATH CONCEPT W/GARRETT PM GENERATOR AND PM TRACTION MOTORS

ELECTRIC TRANSMISSION CHARACTERISTICS

VEHICLE GVW 40 TON

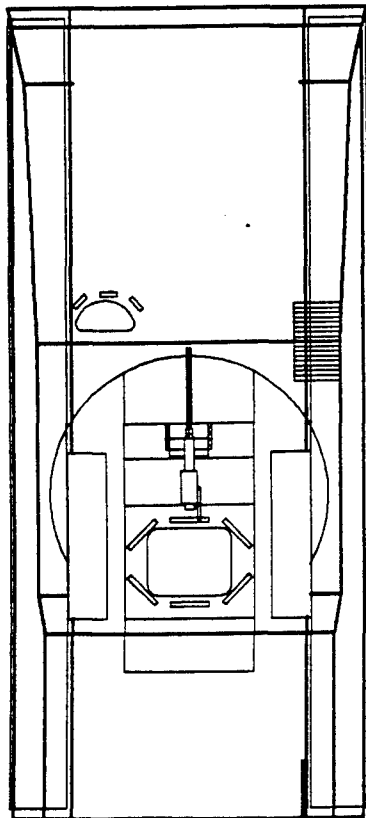
CONF. IV

CONCEPT 2

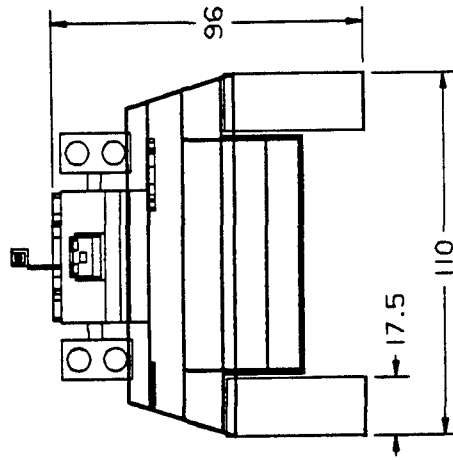
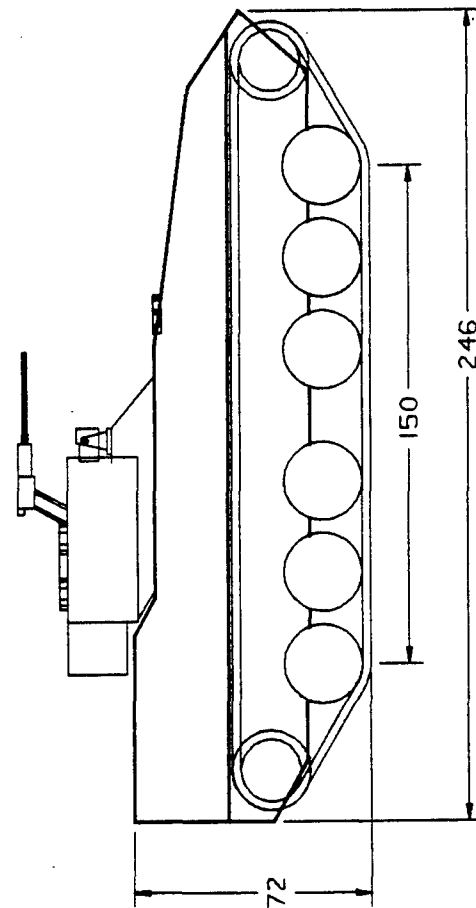
Units Req'd	Unit	Size (In)	Unit Volume Ft ³	System Volume Ft ³	Unit Weight (Lbs)	System Weight (Lbs)	Rating HP	Efficiency %	Remarks
1	Generator	11.2 dia x 15.1		.86	217	217	837	94.5	18000 rpm
1	Rectifier	14.5 x 14.5 x 14.5		1.75	180	180		98	Oil Cooled
4	Motor Controller	12.8 x 12.8 x 12.8	1.20	4.80	75	300	210	98	Oil Cooled
4	Traction Motor	13 dia x 6.5	.50	2.00	110	440	192	94	Elec Shift Air Cooled
1	Single Speed Combining Gearbox	14 dia x 8	.75	1.50	100	200			Variable Ratio
1	ECU	12 x 10 x 12		.80	40	40			
1	Transfer Case w/Clutch & Brake	12 x 12 x 12		1.00	180	180		98	5.6:1 Ratio
1	Cross Drive Gearbox	12 x 12 x 12		1.00	150	150		98	
1	Air & Oil Cooling System			4.00	250	250			
3	Shafts			.40	60	60			
2	Brakes		.40	.80	110	220			
	Cables & Connectors				40	40			
			18.91		2277			85 avg. (82-88)	

UNIQUE MOBILITY SELF-SYNC MOTORS/GARRETT PM GENERATOR

GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPMENT
BASIC 19.5 TON CONCEPT
DWG. NO. AD-8432-0001



NOTE: ALL DIMENSIONS
ARE IN INCHES



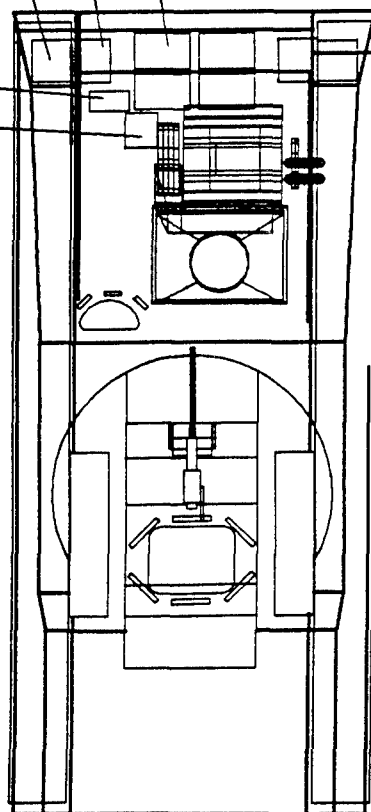
AC GENERATOR

OIL RESEVOIR

TWO SPEED GEARBOX
WITH FINAL DRIVE (2)

PM TRACTION MOTOR (2)

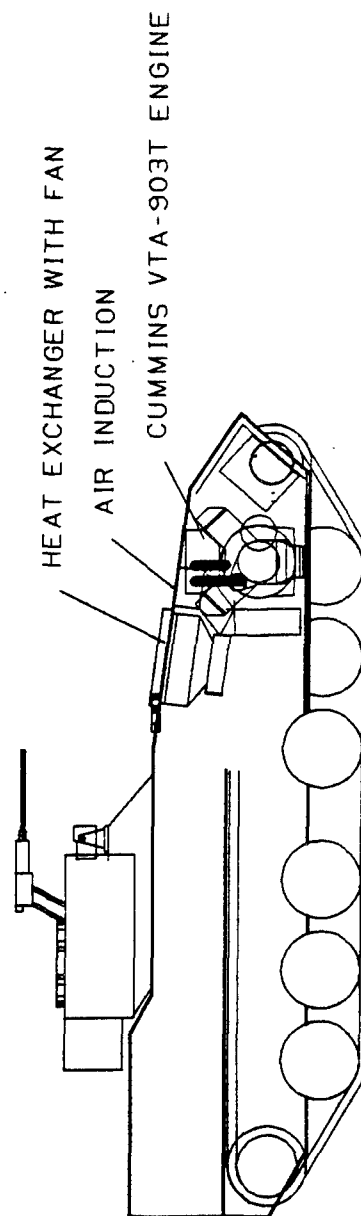
POWER CONDITIONING UNIT (2)



GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON GARRETT
CONCEPT I-1

DWG. NO. AD-8432-0002

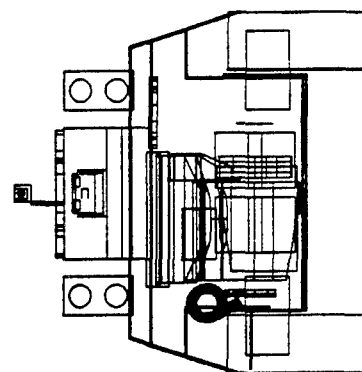
B-40

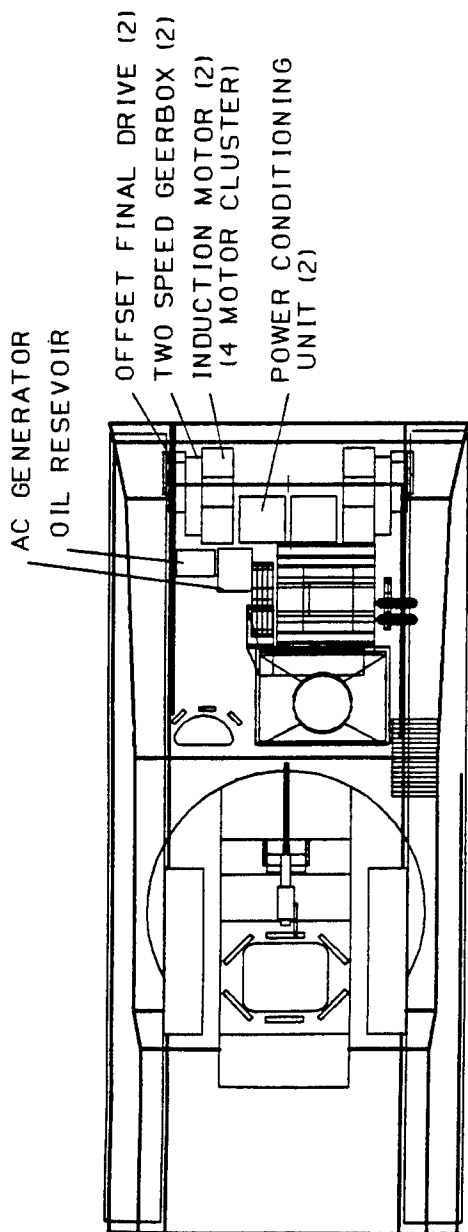


HEAT EXCHANGER WITH FAN

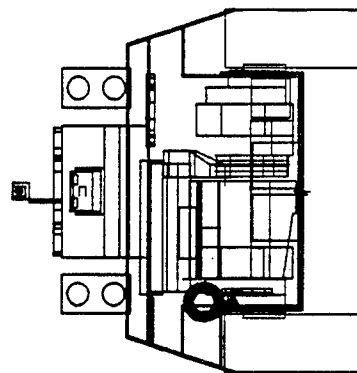
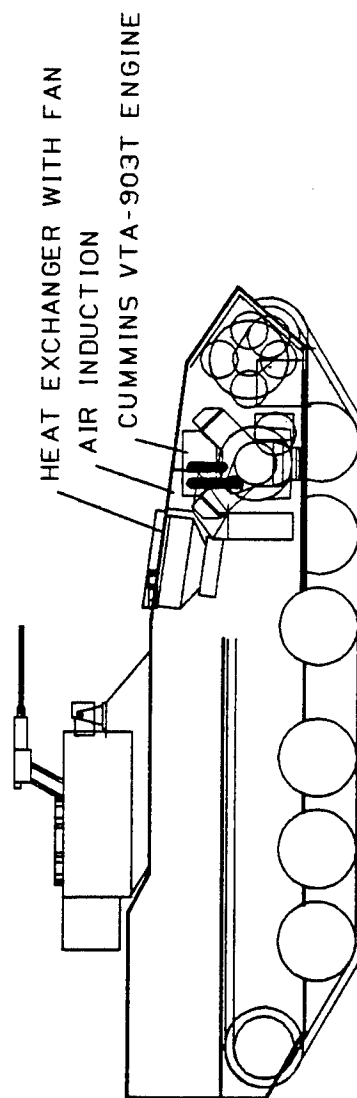
AIR INDUCTION

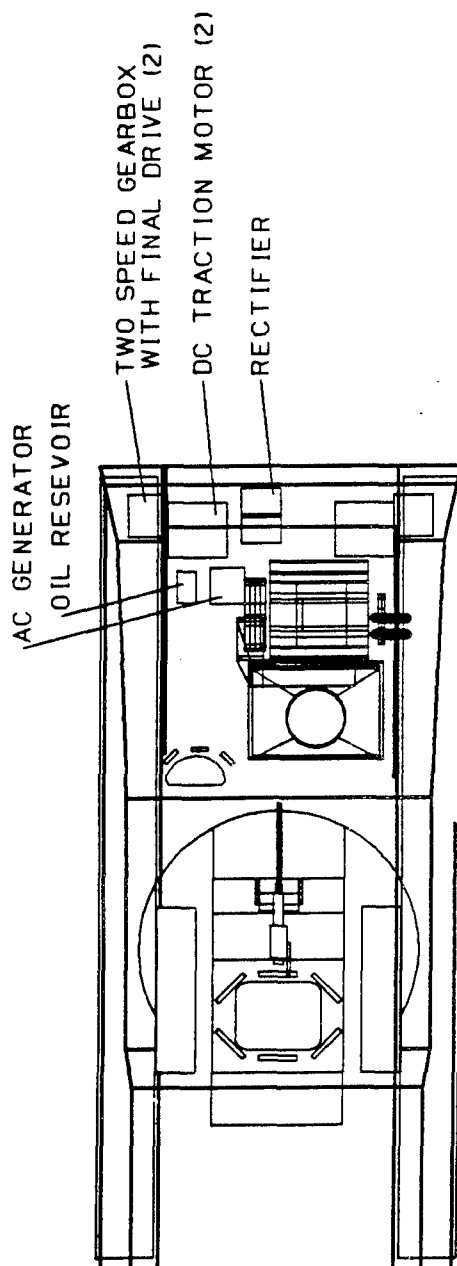
CUMMINS VTA-903T ENGINE



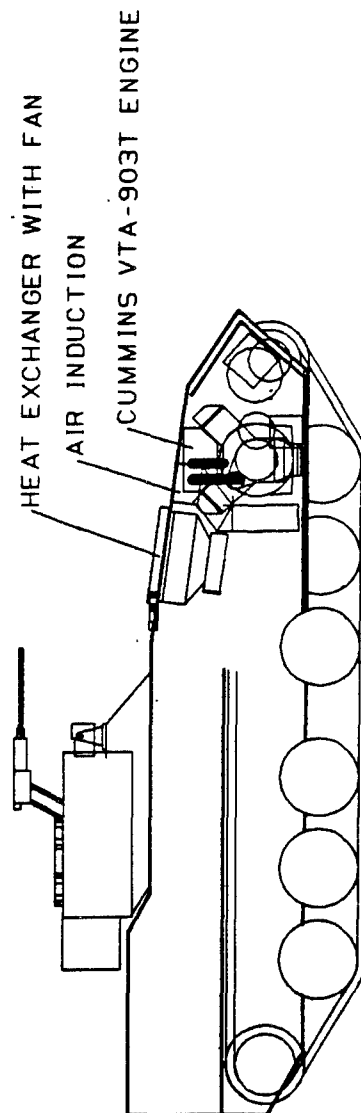
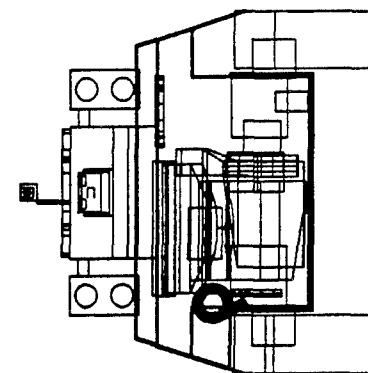


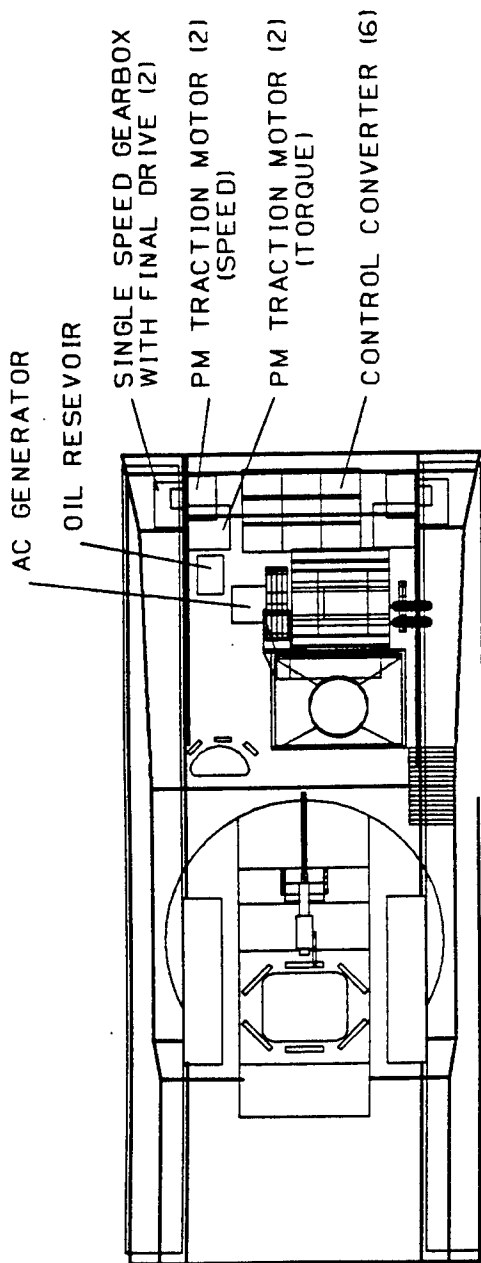
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON WESTINGHOUSE
CONCEPT 1-2
DWG. NO. AD-8432-0003



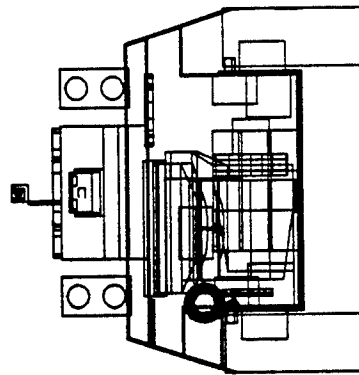
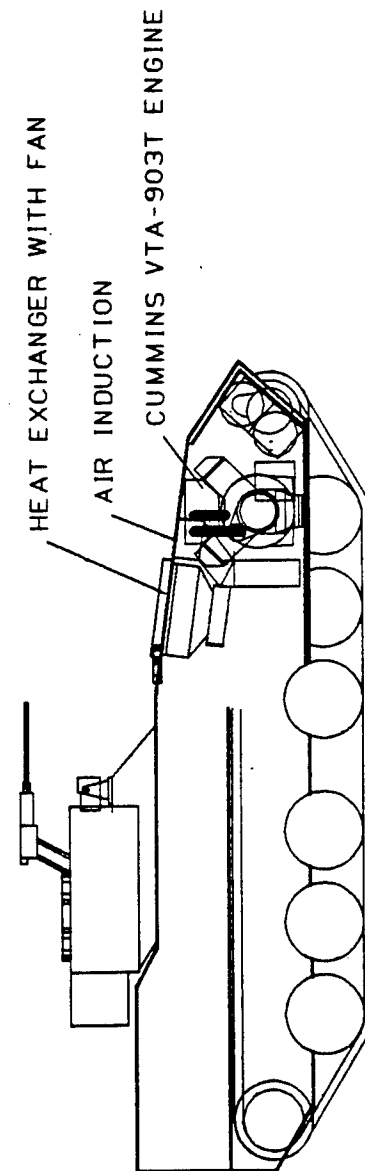


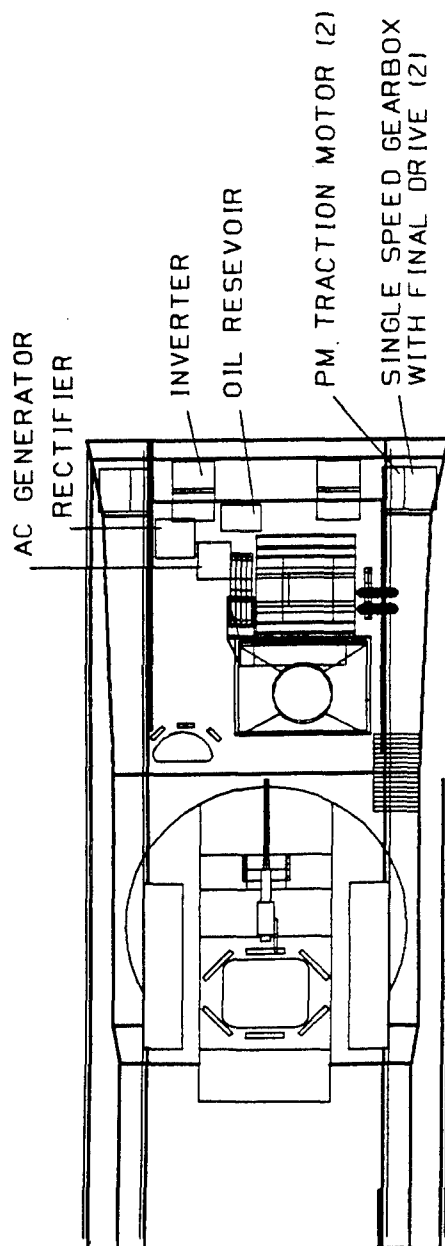
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON ACEC
CONCEPT 1-5
DWG. NO. AD-8432-0023





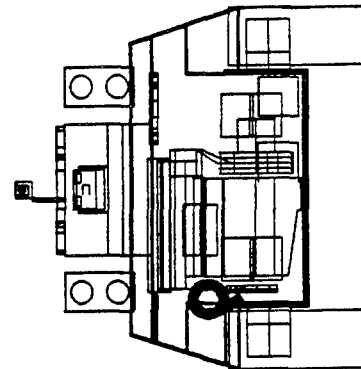
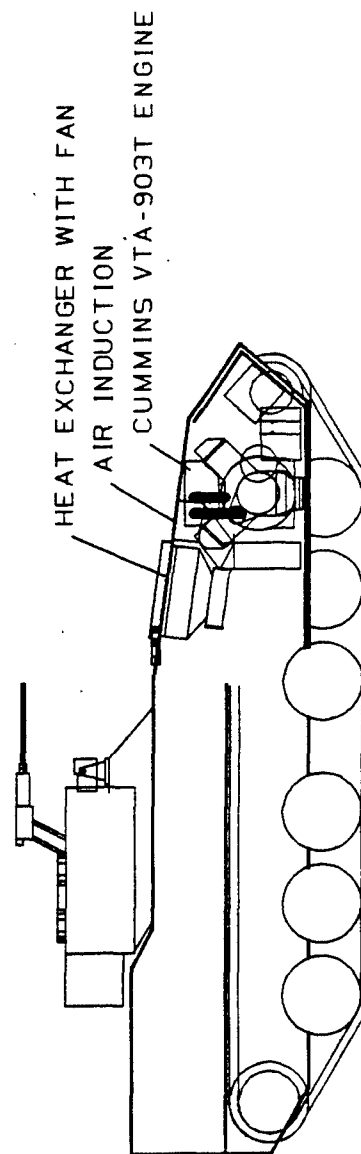
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON GARRETT
CONCEPT I-6
DWG.NO. AD-8432-0004

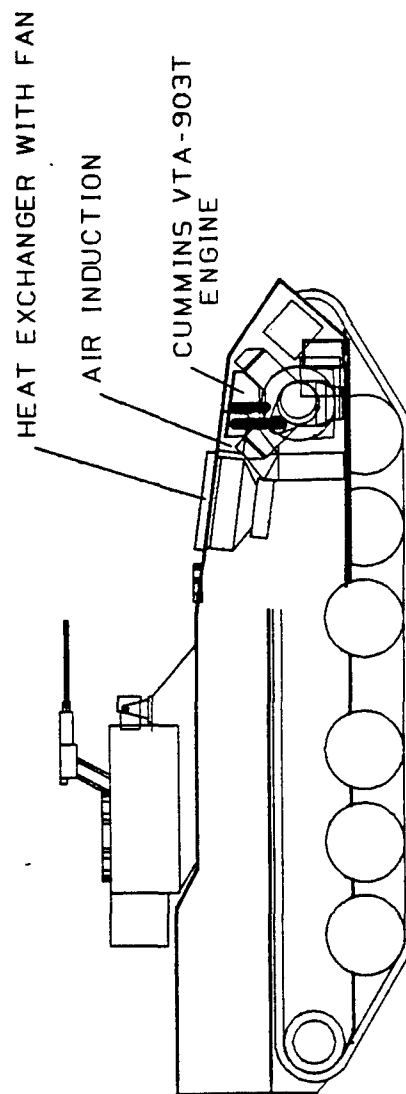
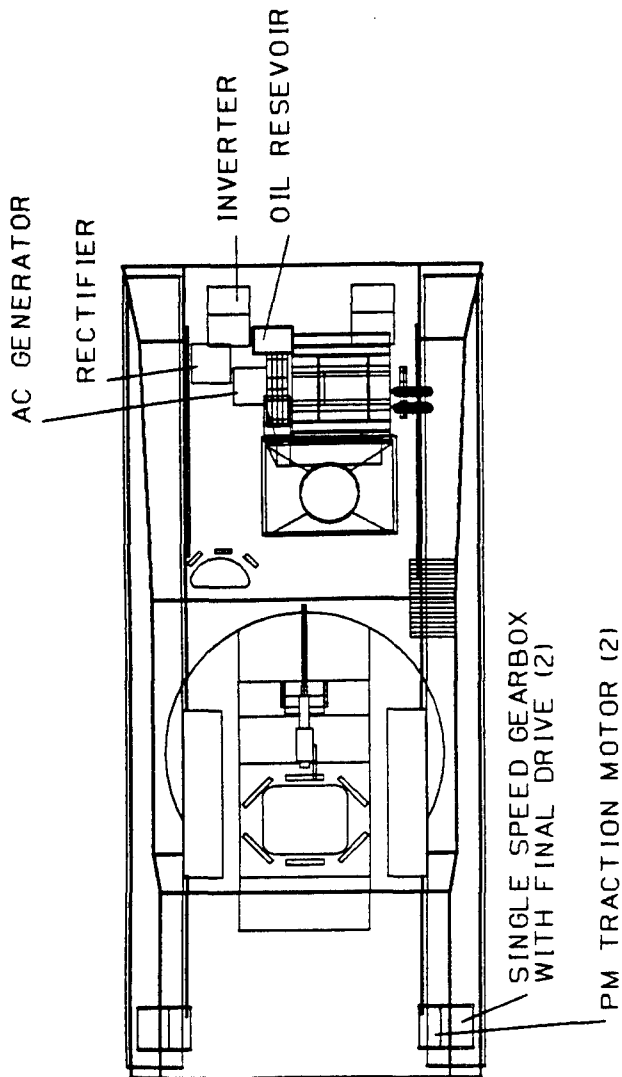




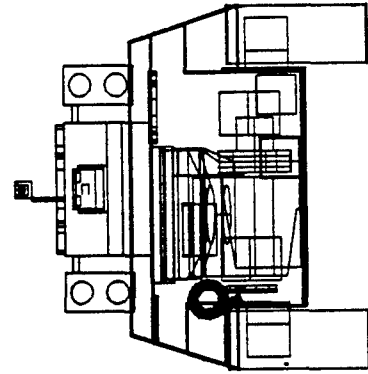
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON UNIQUE MOBILITY
CONCEPT 1-9

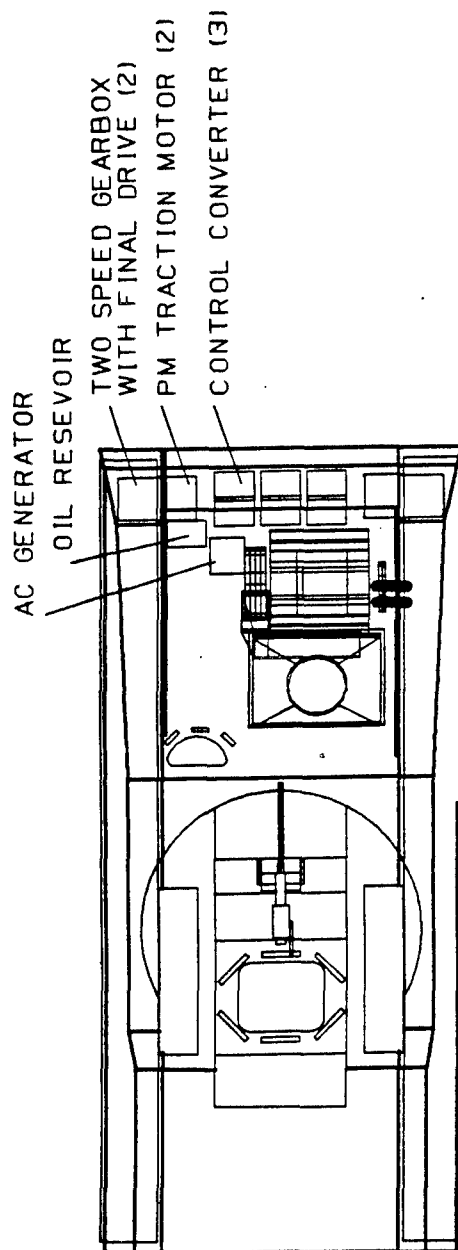
DWG. NO. AD-8432-0005





GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON UNIQUE MOBILITY
CONCEPT I-9A
DWG. NO. AD-8432-0006



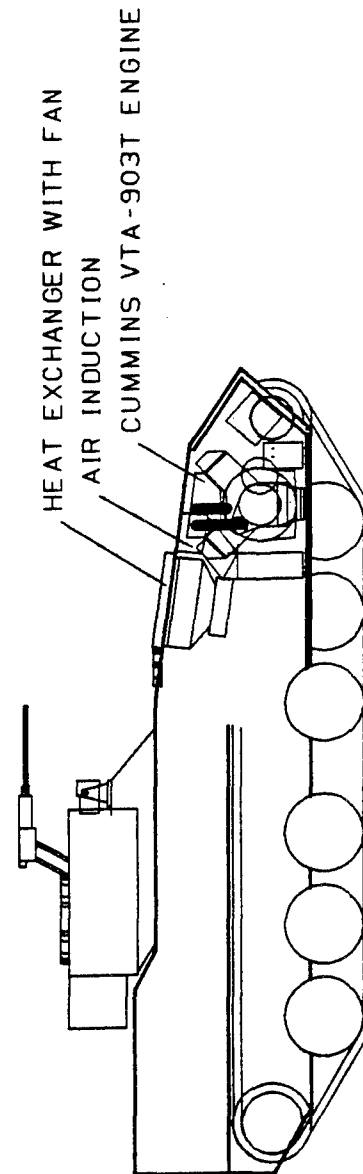
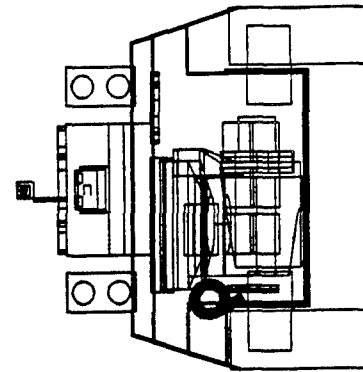


GENERAL DYNAMICS
LAND SYSTEMS DIVISION

ADVANCED DEVELOPEMENT

19.5 TON GARRETT
CONCEPT I-10

DWG. NO. AD-8432-0007



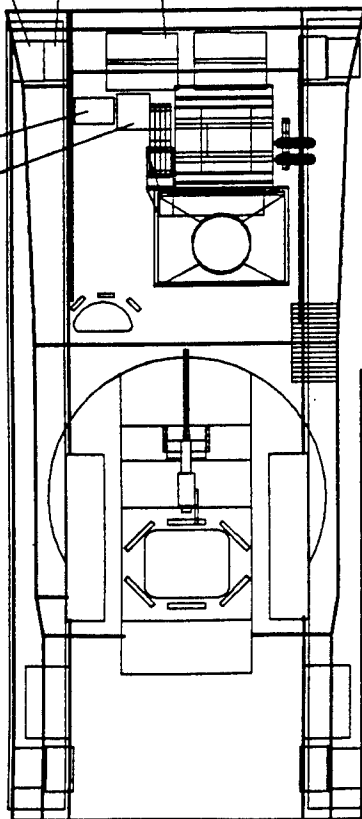
AC GENERATOR

OIL RESEVOIR

TWO SPEED GEARBOX
WITH FINAL DRIVE (4)

PM TRACTION MOTOR (4)

POWER CONDITIONING
UNIT (4)

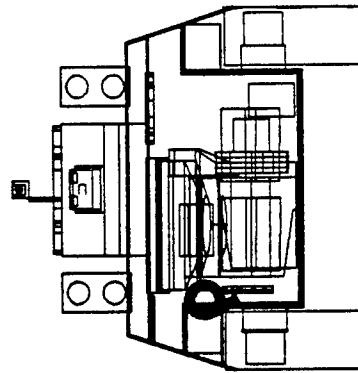
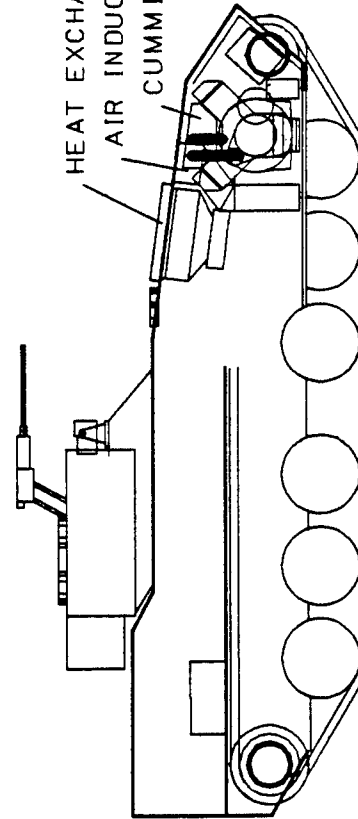


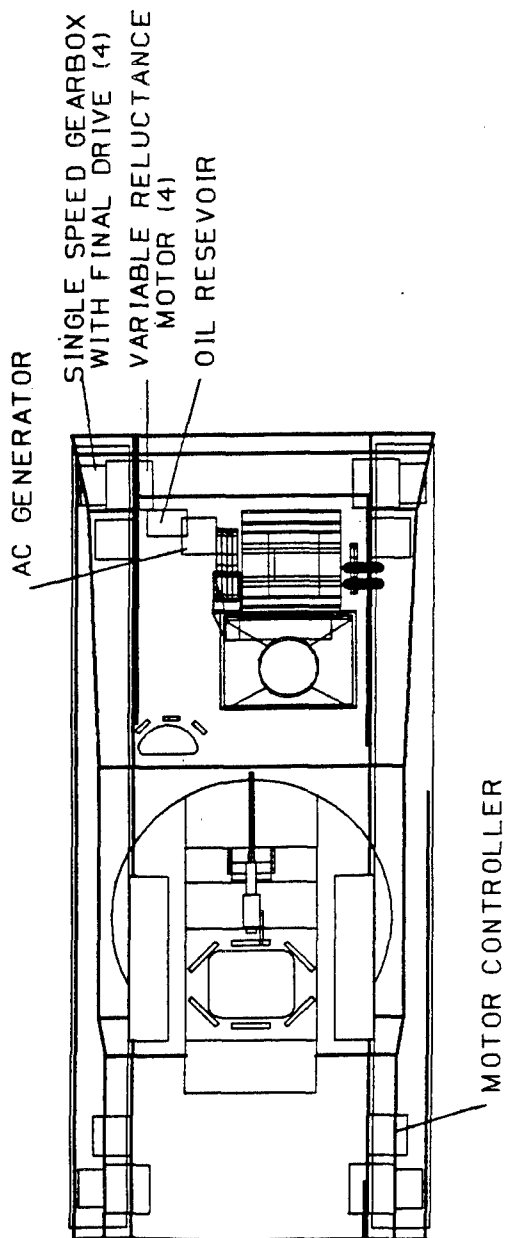
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON GARRETT
CONCEPT IA-1
DWG NO AD-8432-0008

HEAT EXCHANGER WITH FAN

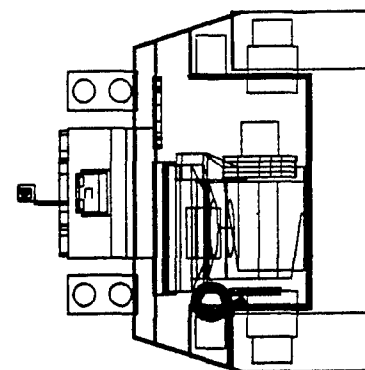
AIR INDUCTION

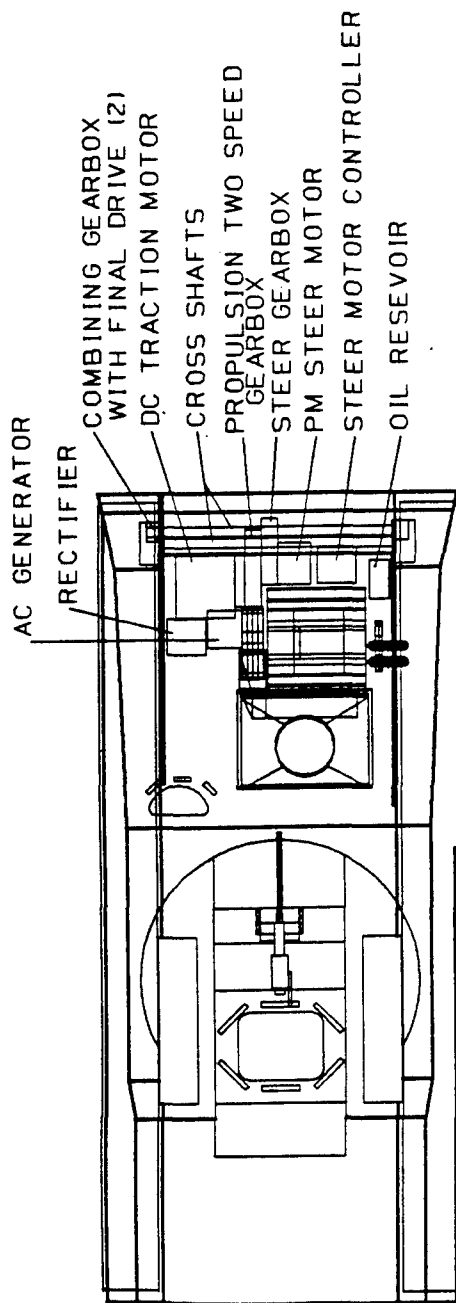
CUMMINS VTA-903T ENGINE



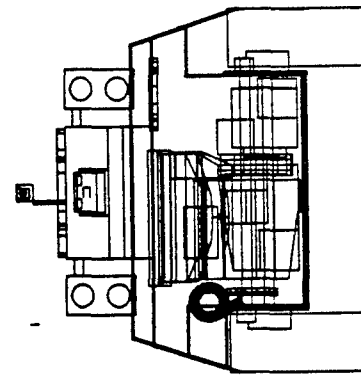
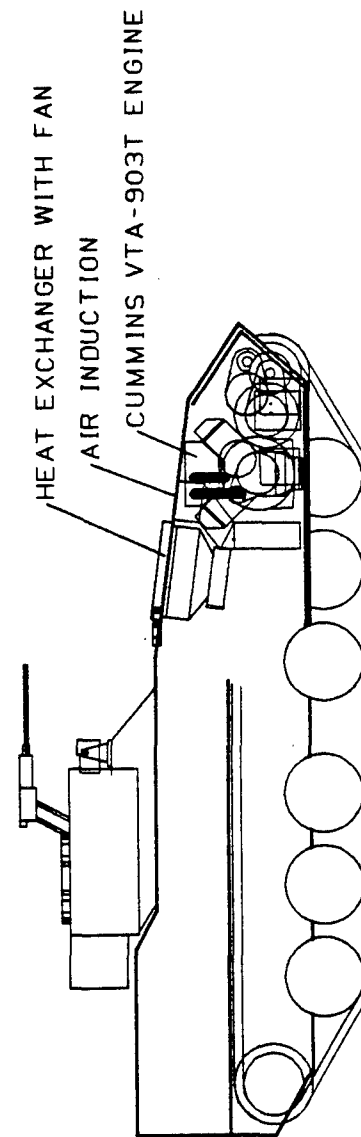


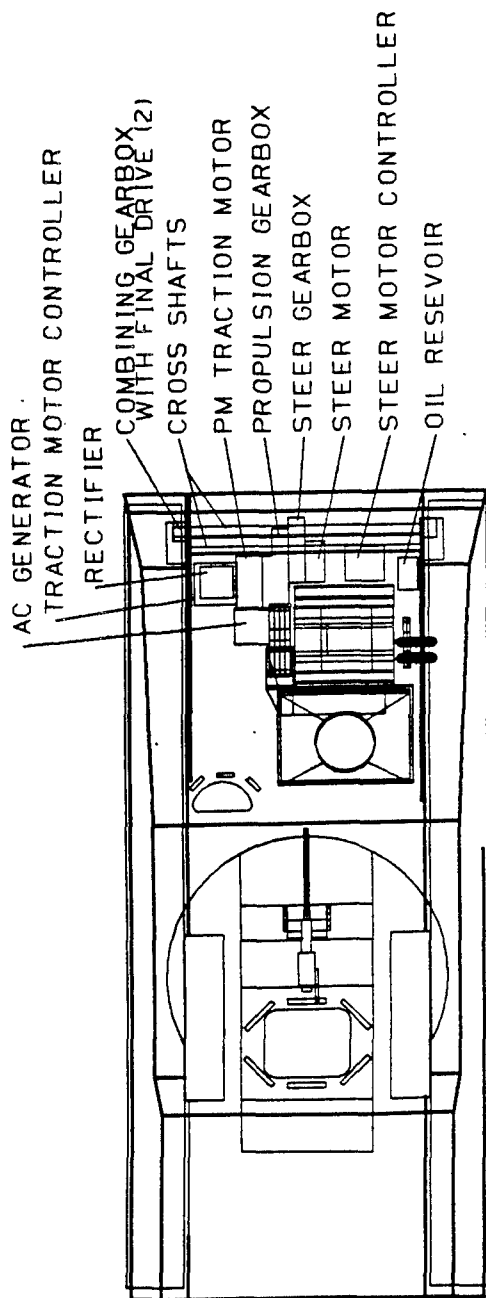
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON JARRET
CONCEPT 1A-3
DWG. NO. AD-8432-0009



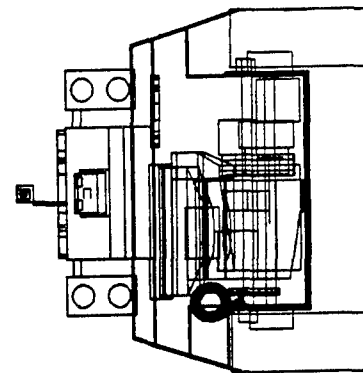
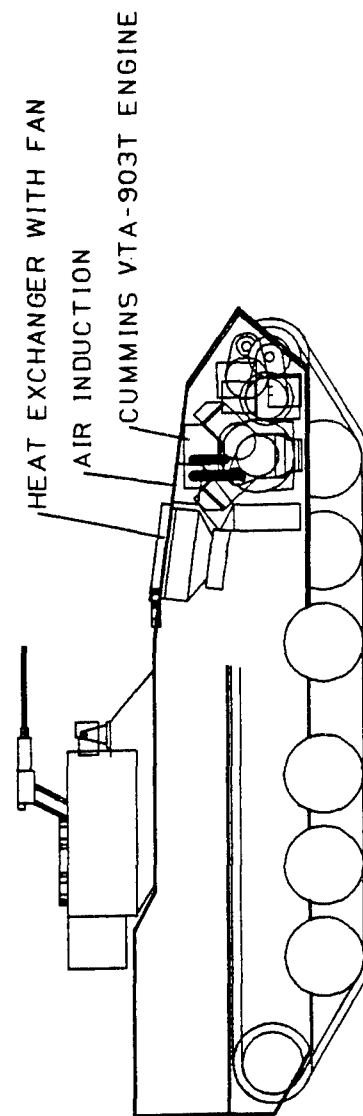


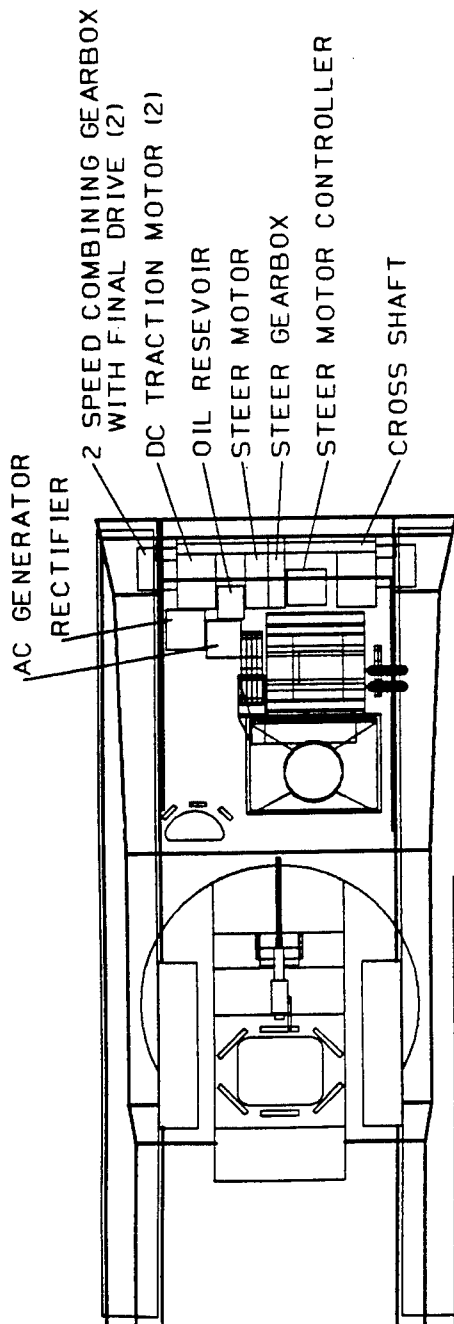
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON UNIQUE MOBILITY
CONCEPT II-3
DWG. NO. AD-8432-0010



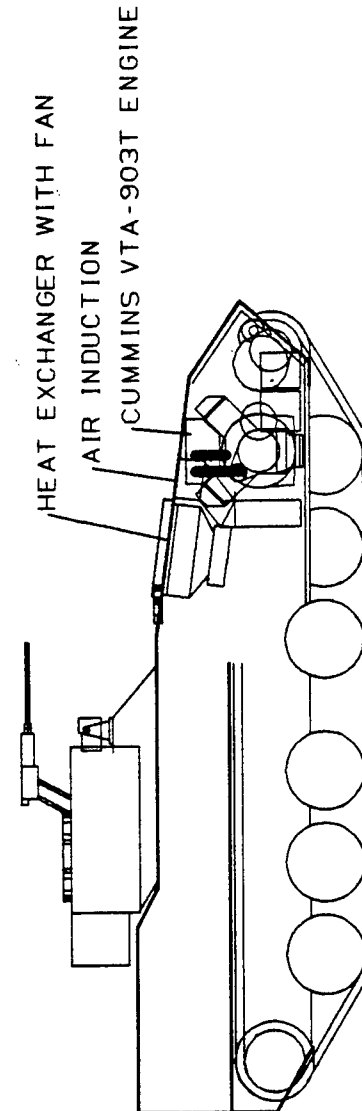
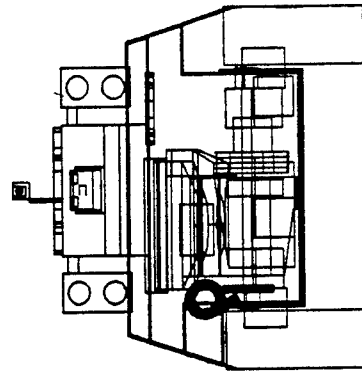


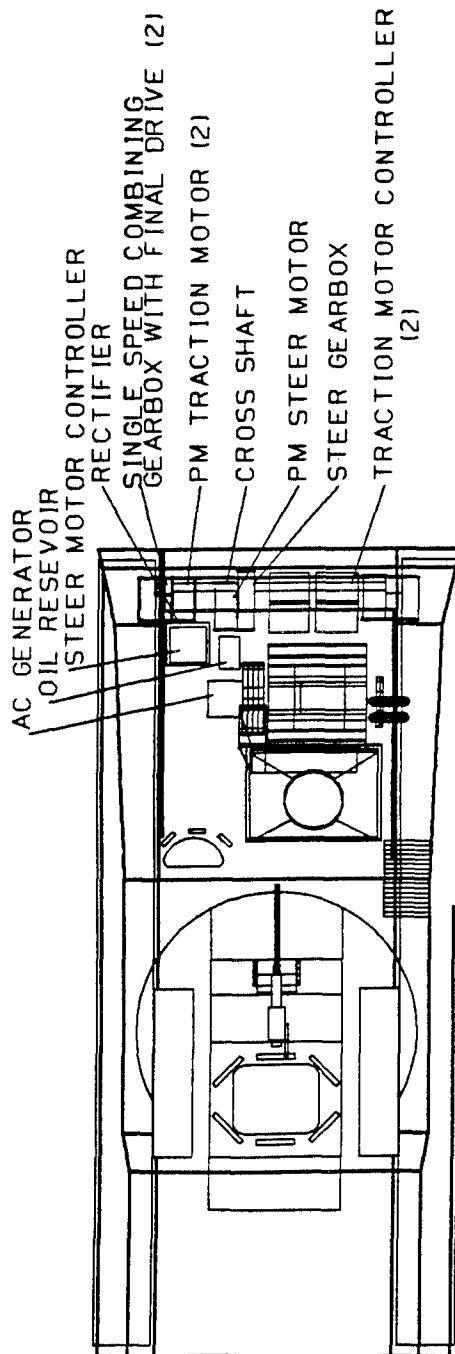
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON UNIQUE MOBILITY
CONCEPT II-6
DWG. NO. AD-8432-0011



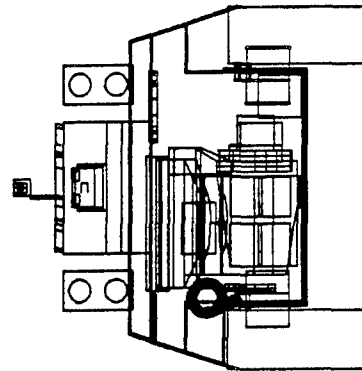
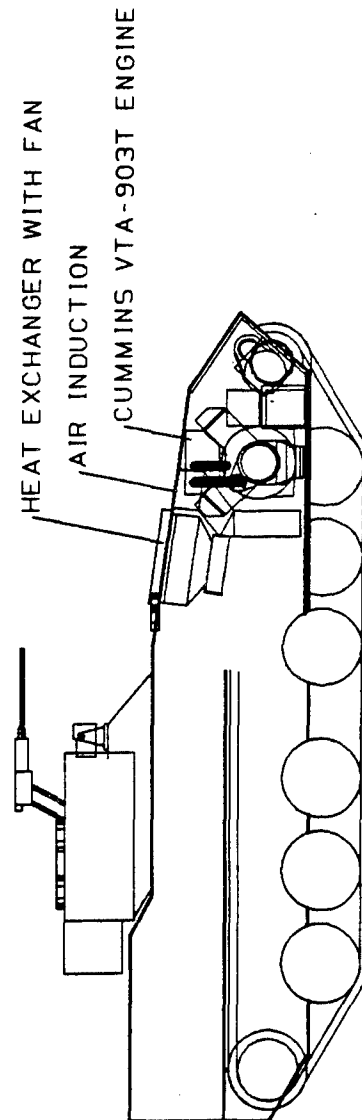


GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON ACEC
CONCEPT III-2
DWG. NO. AD-8432-0012





GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON UNIQUE MOBILITY
CONCEPT III-3
DWG. NO. AD-8432-0013



RIGHT ANGLE GEARBOX

AC GENERATOR

RECTIFIER

SINGLE SPEED COMBINING
GEARBOX WITH FINAL DRIVE (2)

PM TRACTION MOTOR (2)

OIL RESEVOIR

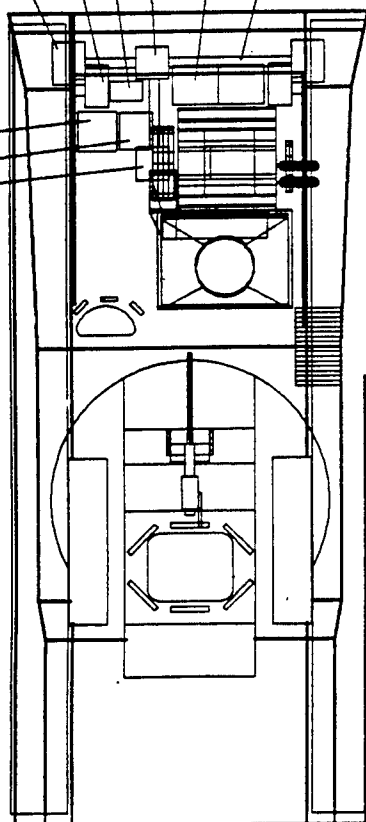
CROSS DRIVE GEARBOX

MOTOR CONTROLLER (2)

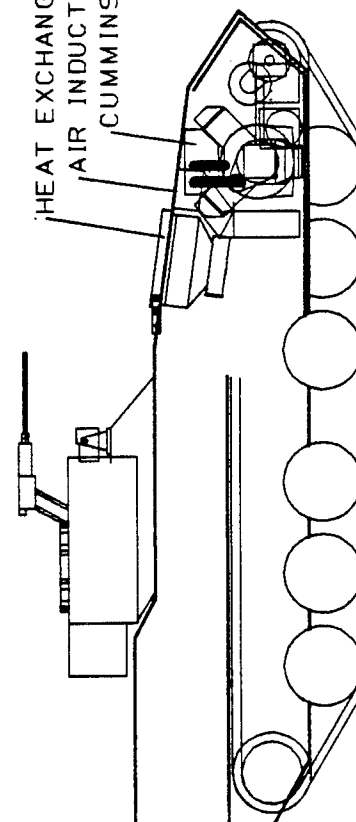
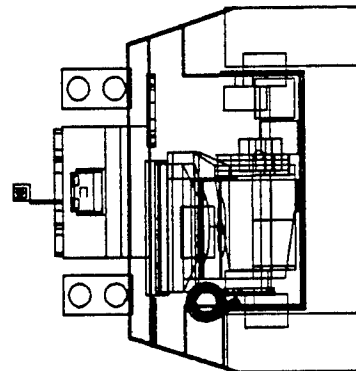
CROSS SHAFT

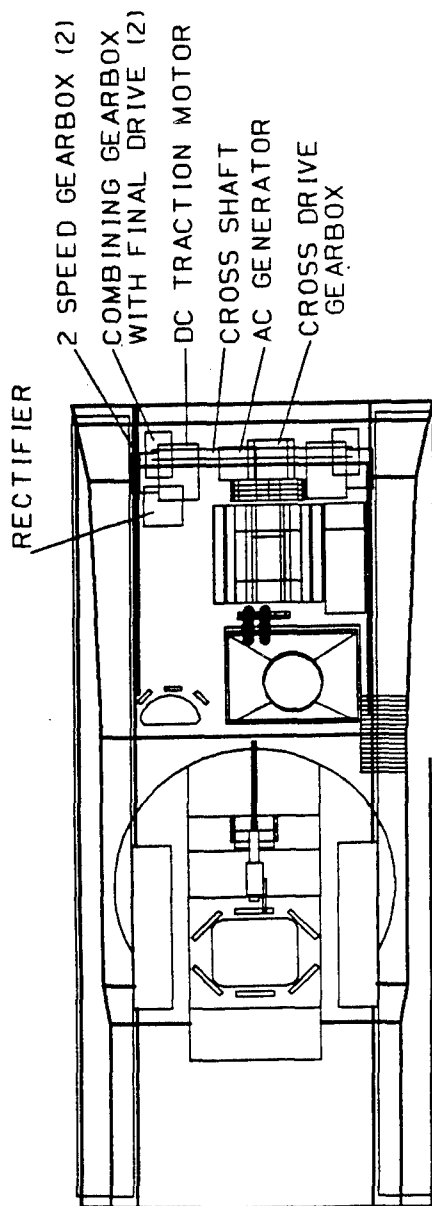
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON UNIQUE MOBILITY
CONCEPT IV-2

DWG. NO. AD-8432-0014

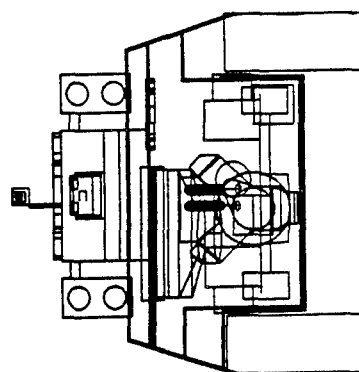


HEAT EXCHANGER WITH FAN
AIR INDUCTION
CUMMINS VTA-903T ENGINE





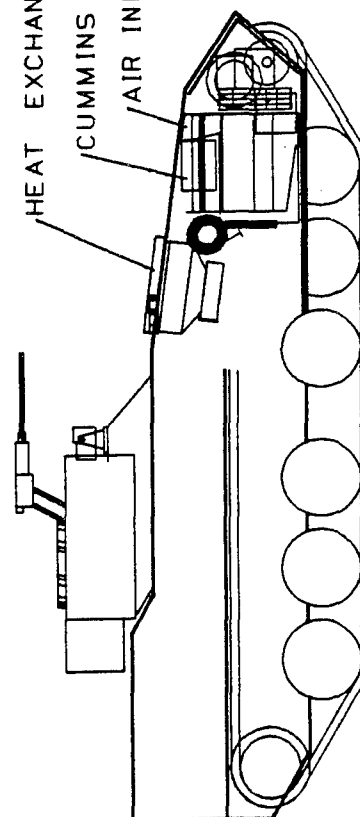
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
19.5 TON ACEC
CONCEPT IV-3
DWG. NO. AD-8432-0015



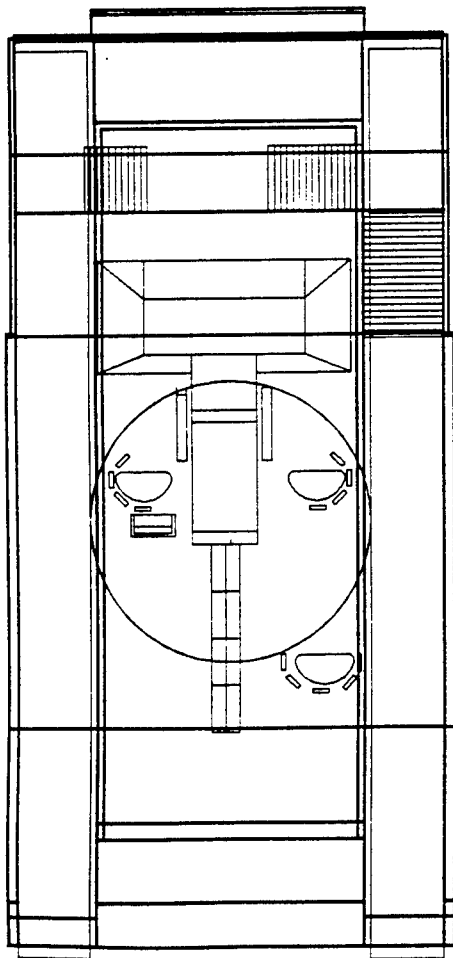
HEAT EXCHANGER WITH FAN

CUMMINS VTA-903T ENGINE

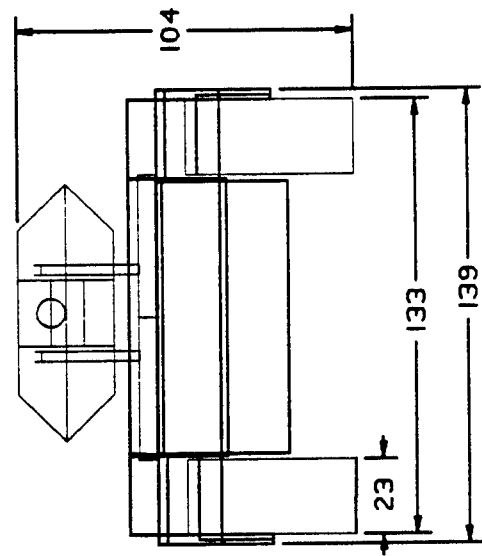
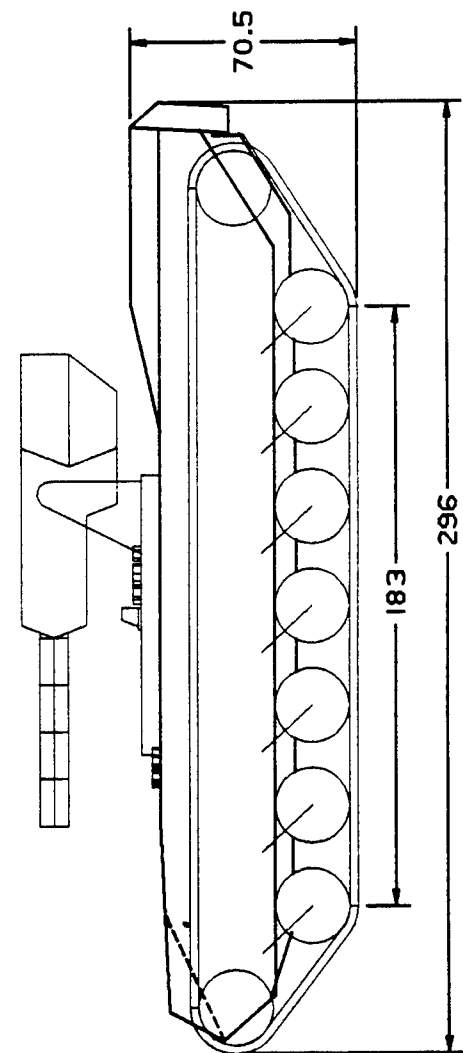
AIR INDUCTION



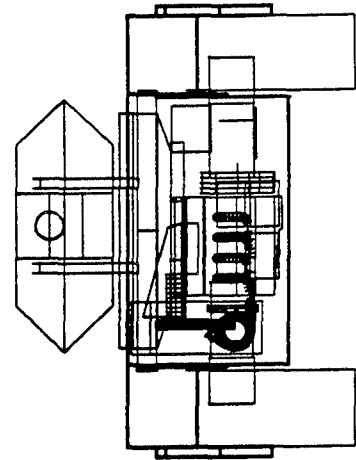
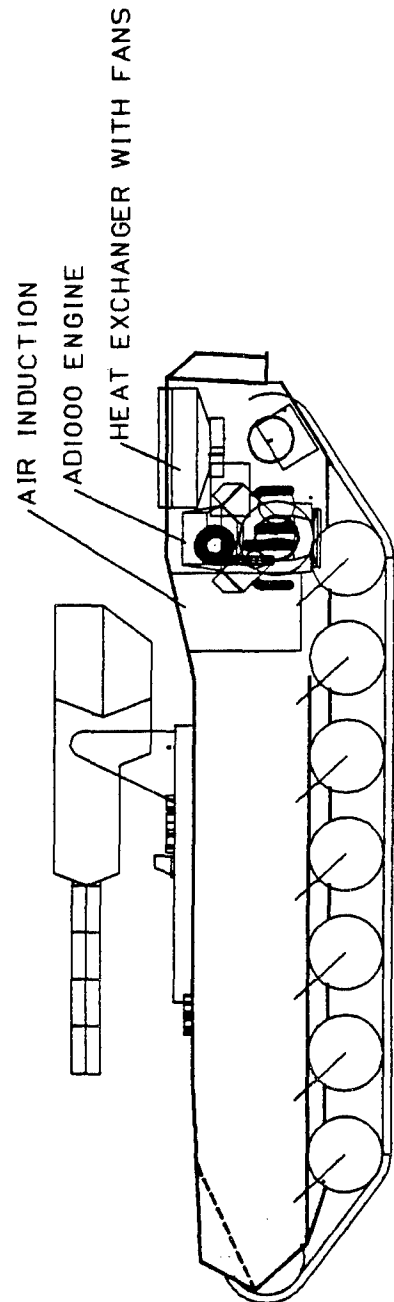
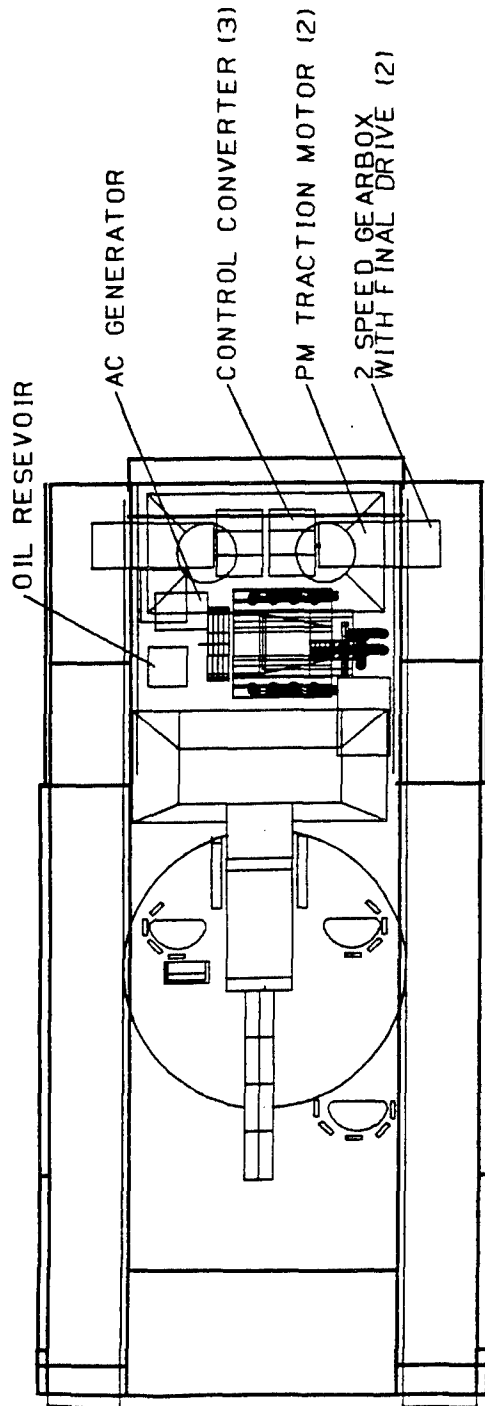
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
BASIC 40 TON CONFIGURATION
DWG. NO. AD-8432-0016

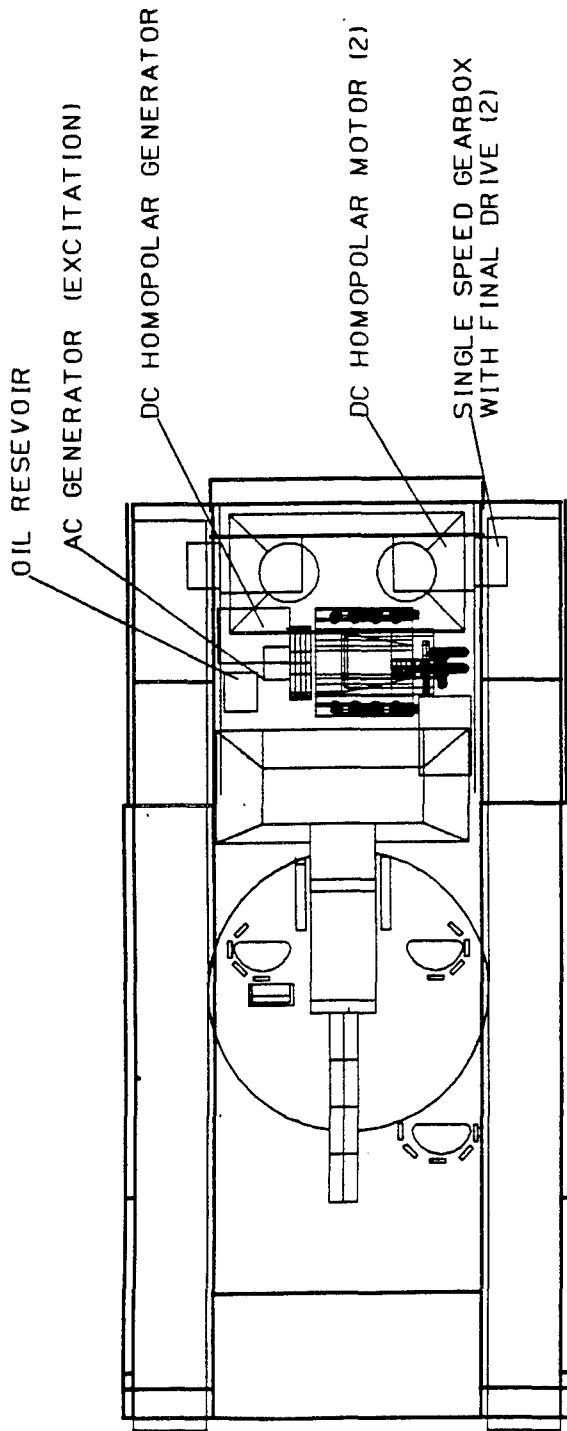


NOTE: ALL DIMENSIONS
ARE IN INCHES



GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
40 TON GARRETT
CONCEPT I-3
DWG. NO. AD-8432-0017





OIL RESEVOIR

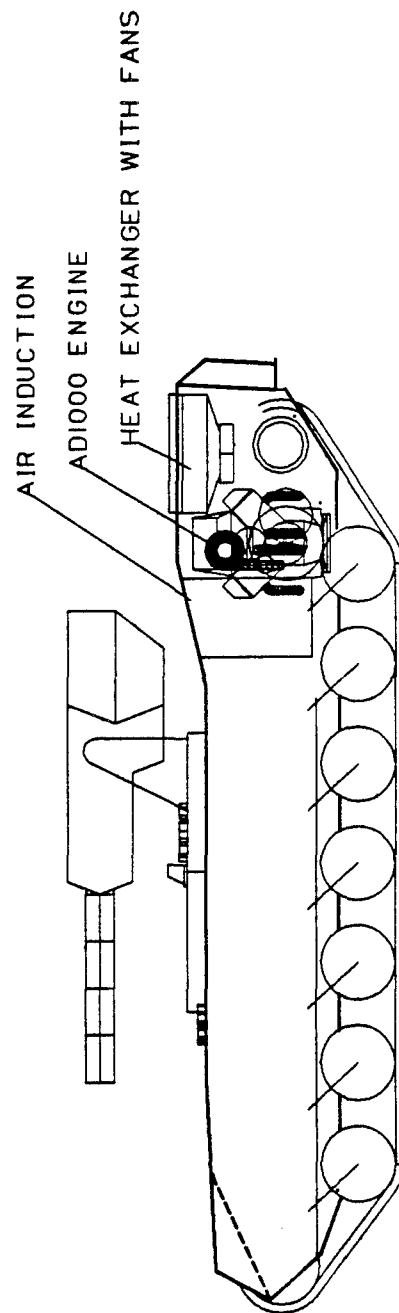
AC GENERATOR (EXCITATION)

DC HOMOPOLAR GENERATOR

DC HOMOPOLAR MOTOR (2)

SINGLE SPEED GEARBOX
WITH FINAL DRIVE (2)

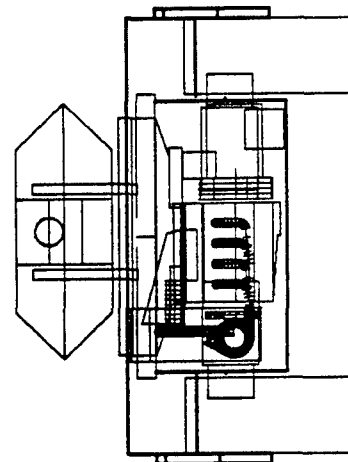
GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
40 TON WESTINGHOUSE
CONCEPT I-4
DWG. NO. AD-8432-0018



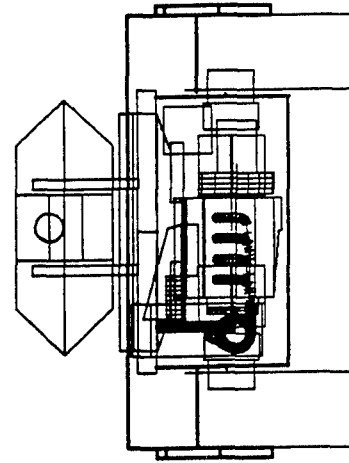
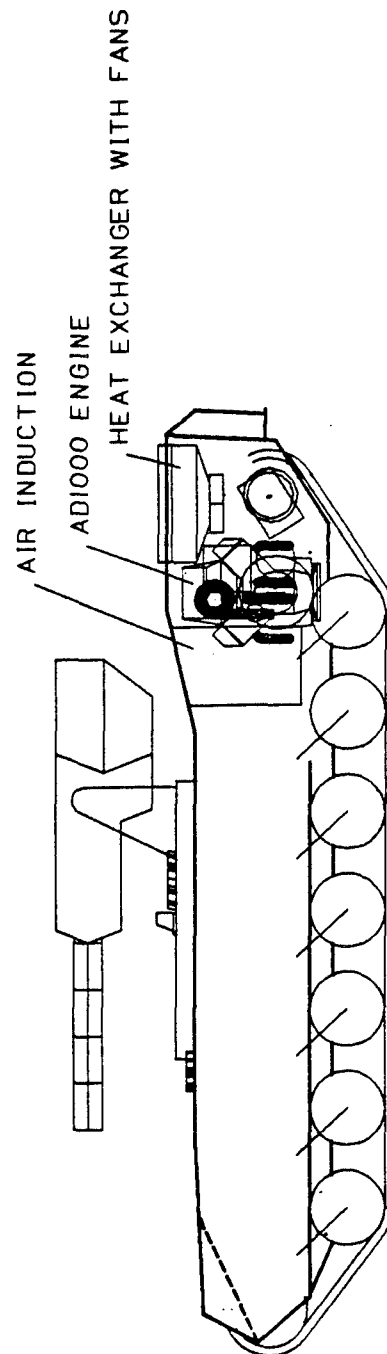
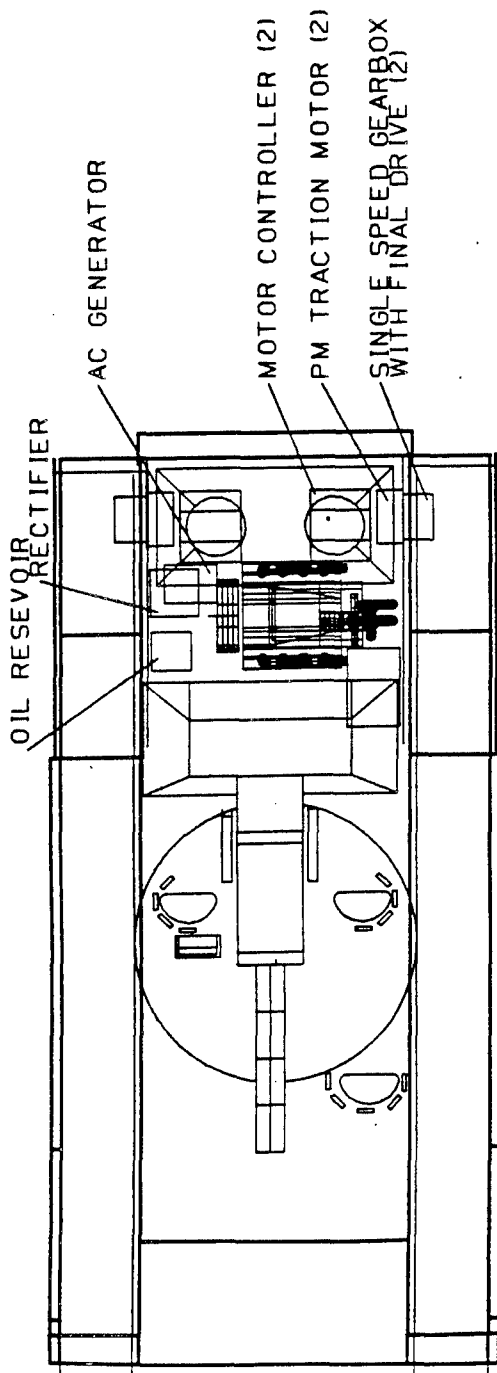
AIR INDUCTION

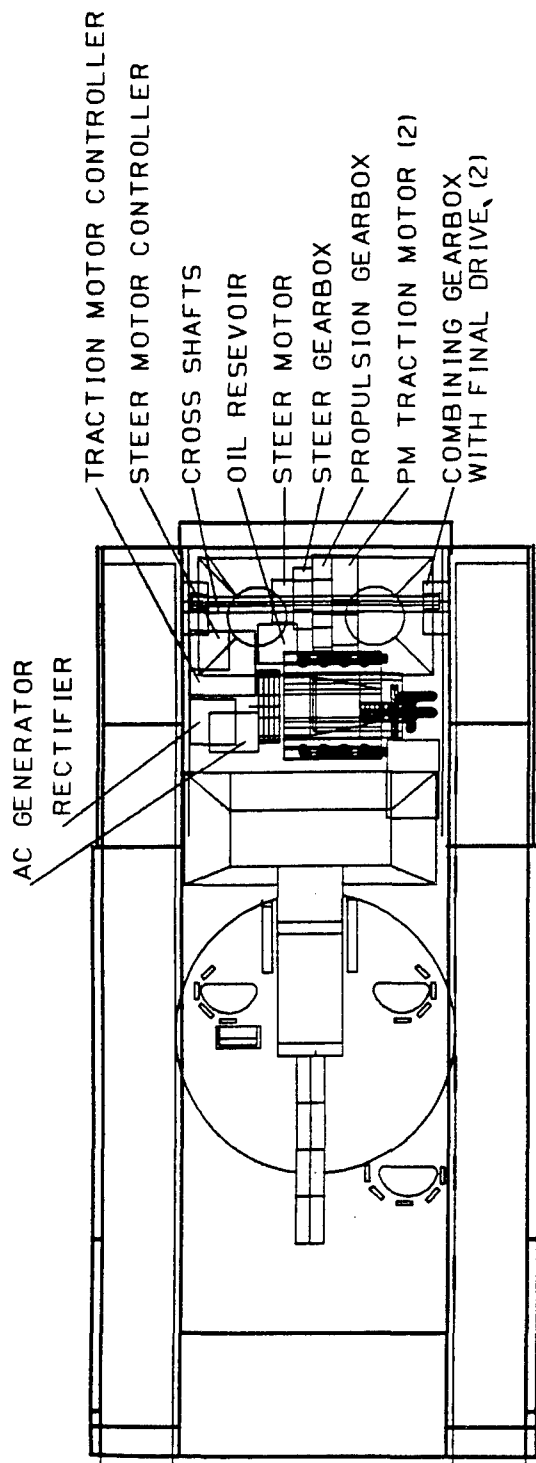
AD1000 ENGINE

HEAT EXCHANGER WITH FANS



GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
40 TON UNIQUE MOBILITY
CONCEPT 1-6
DWG. NO. AD-8432-0019



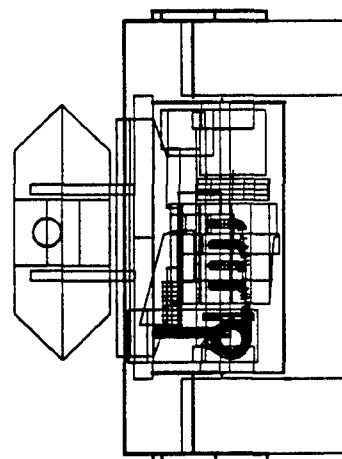
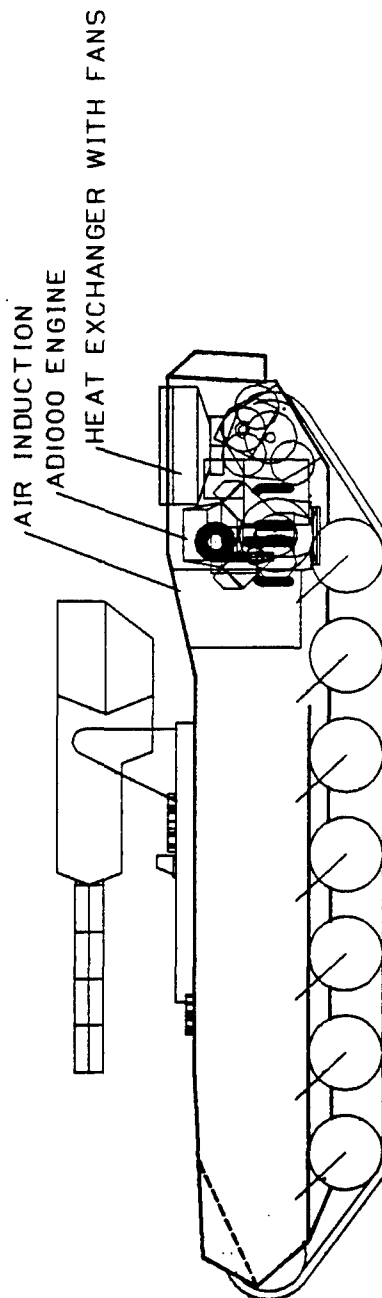


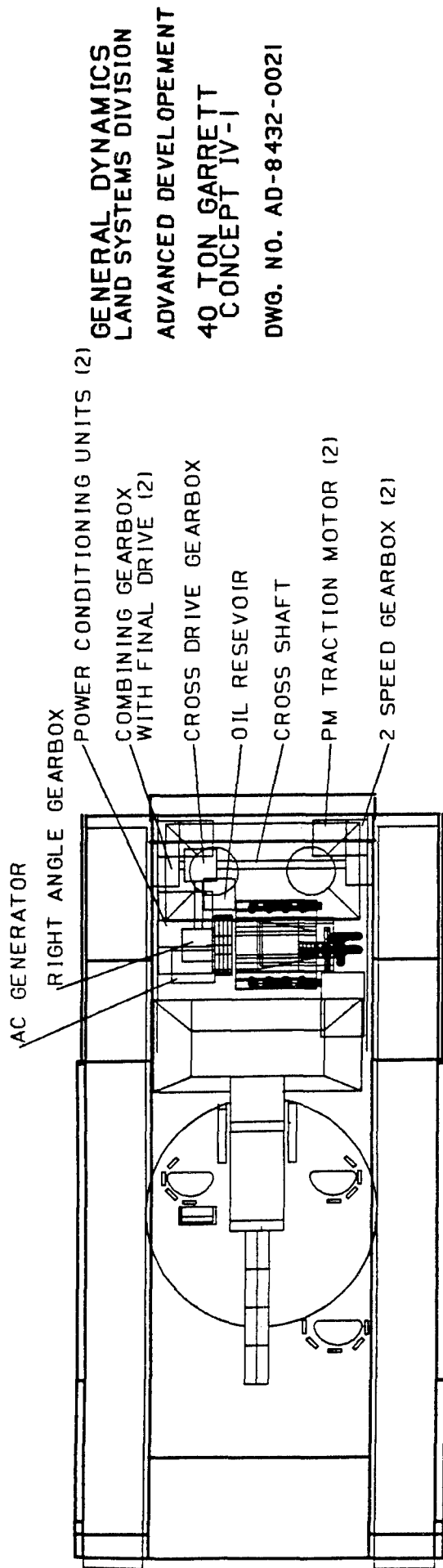
GENERAL DYNAMICS
LAND SYSTEMS DIVISION

ADVANCED DEVELOPEMENT

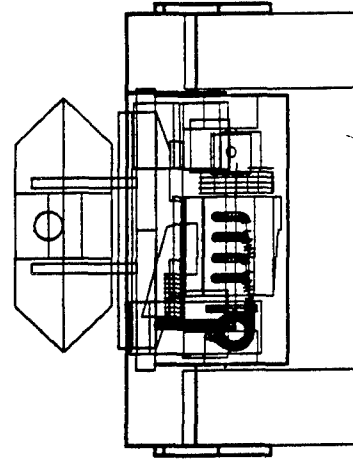
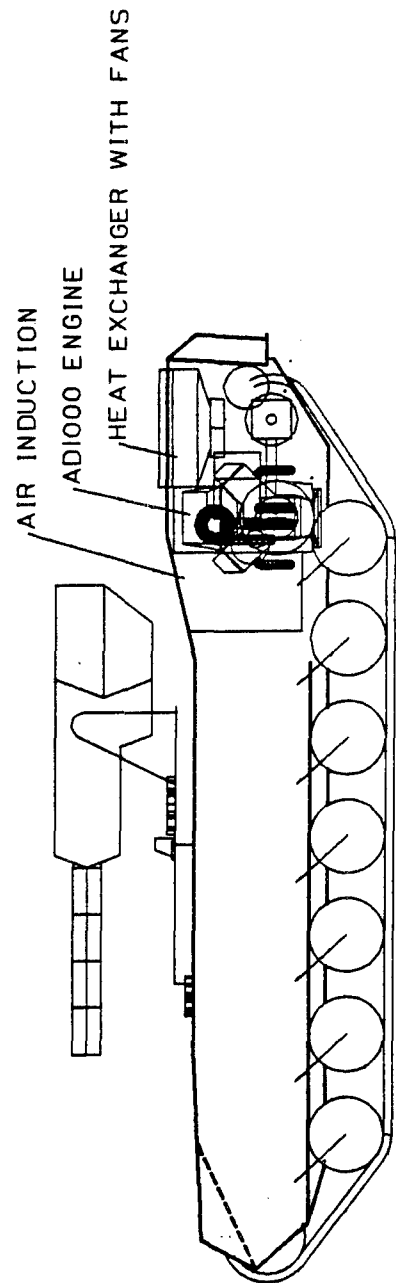
40 TON UNIQUE MOBILITY
CONCEPT II-4

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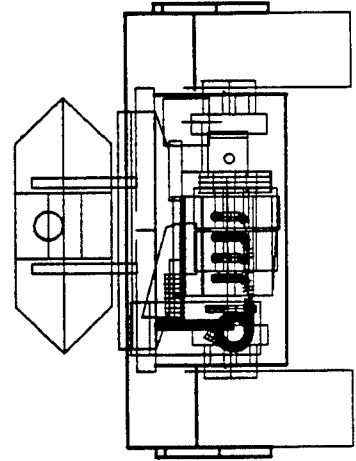
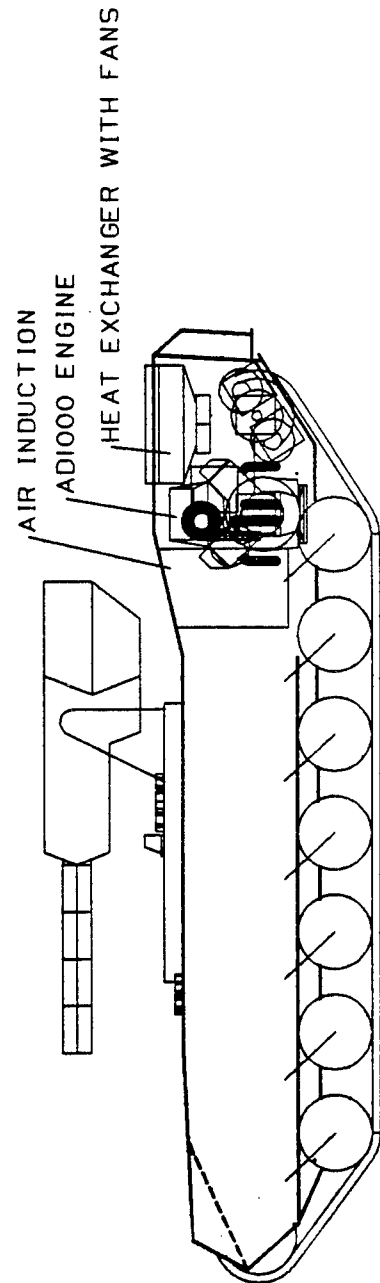
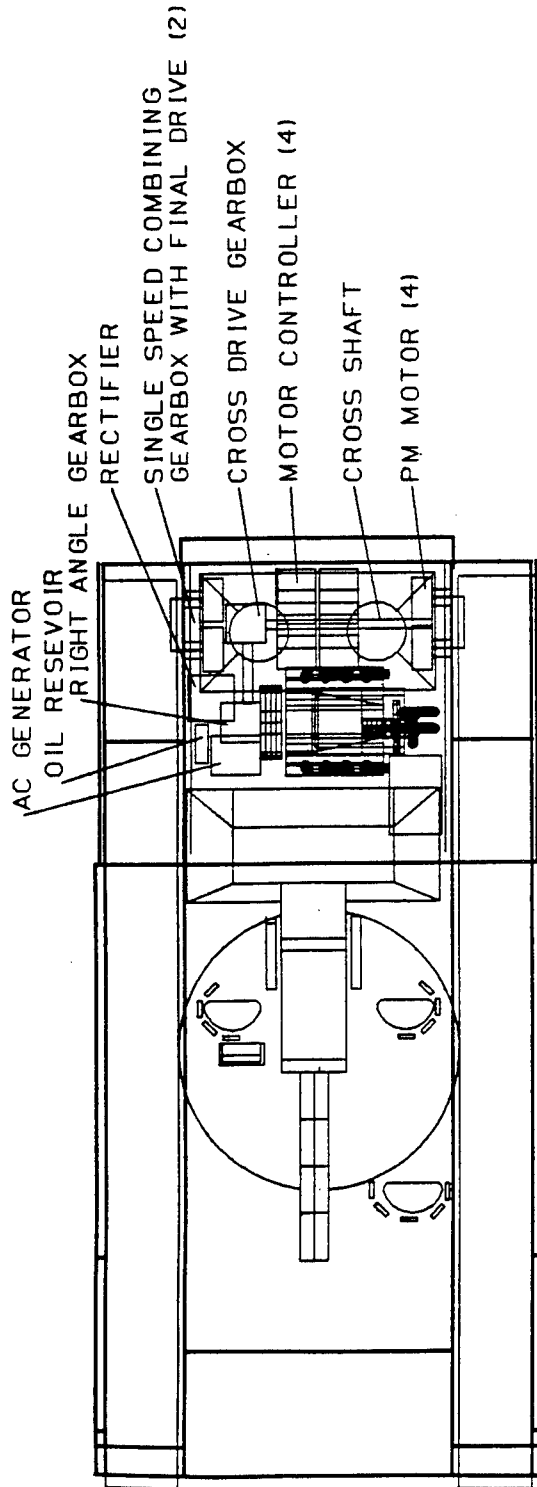


GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
40 TON GARRETT
CONCEPT IV-1
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GENERAL DYNAMICS
LAND SYSTEMS DIVISION
ADVANCED DEVELOPEMENT
40 TON UNIQUE MOBILITY
CONCEPT IV-2

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